Search for Conical Emission in A + A collisions

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- Search Method
- Cumulant Definition
- No Such A Thing As ZYAM
- Sensitivity to Conical Emission
- STAR results
- Summary

The Robustness of a Discovery is only as strong as the assumptions used to achieve this discovery.

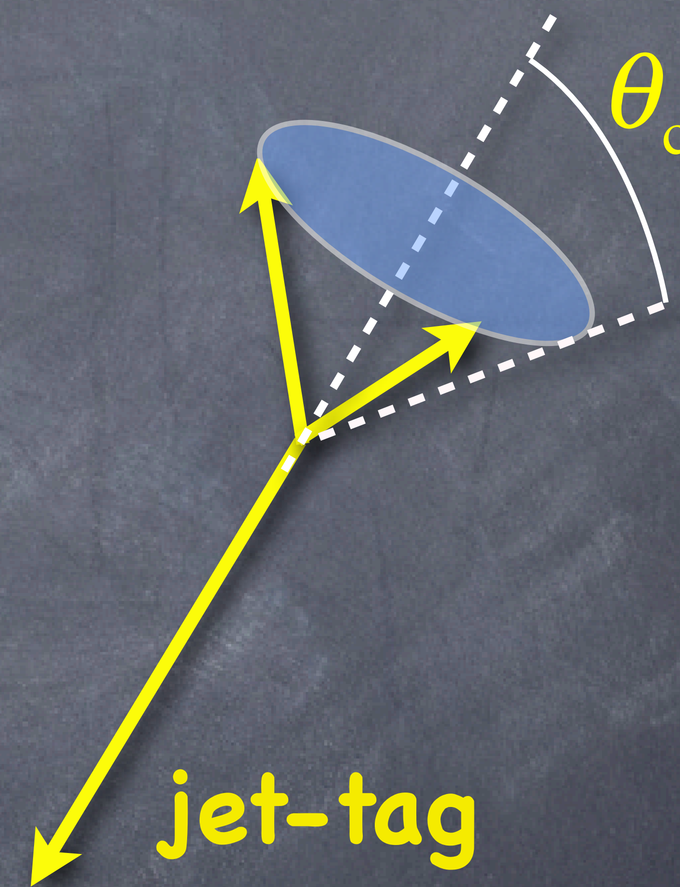
Unfortunately ZYAM is NOT robust.

No Such A Thing As ZYAM

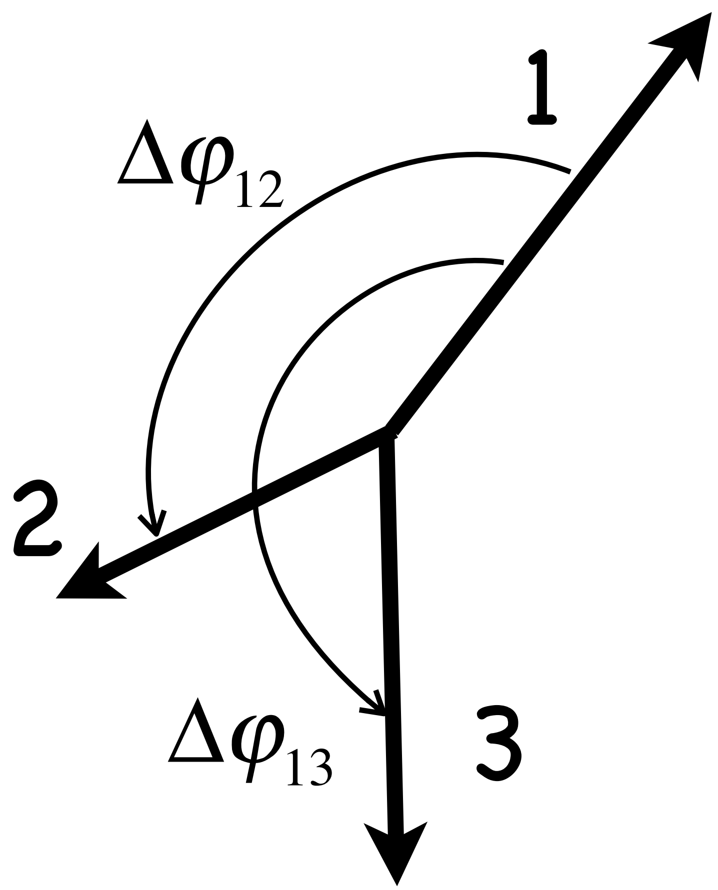
- Two/Three Particle Decays
- Anisotropic Flow Effects
- Momentum/Energy Conservation
- Radial Flow Effects
- p+p is never really gone:
  - Surface Bias
  - Core vs corona correlations
  - Which dominates?
  - Corona correlations may be modified by flow, scattering, absorption, etc

Cone Search Methods

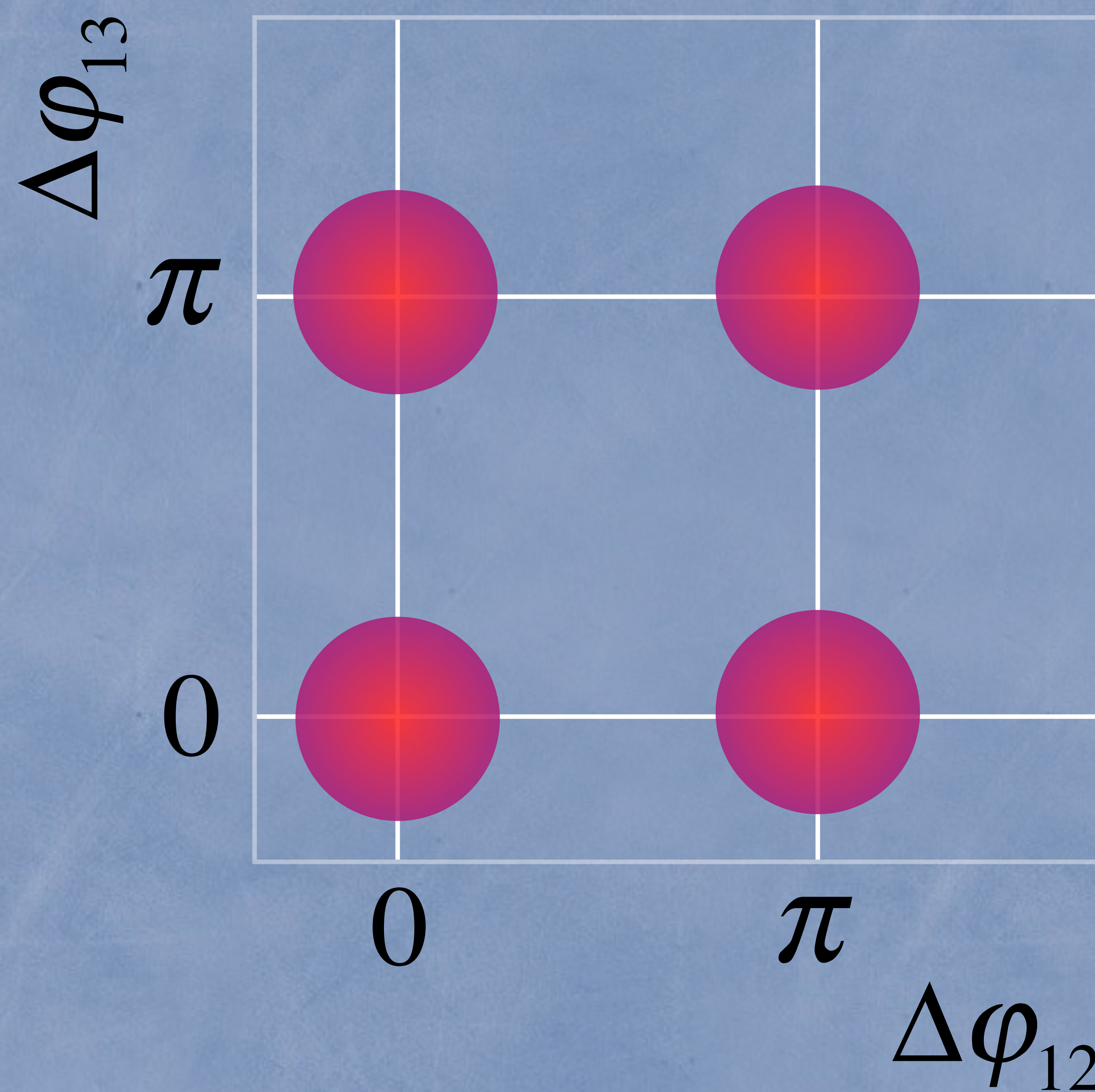
- Use **one high-pt particle** to identify a jet candidate,
  - Trigger particle or **jet-tag**
- Use **two "low-pt" away-side particles** to identify a cone.
  - Transverse Plane
  - Azimuthal Coordinates



Conical Emission Signature



1: Jet Tag
2,3: Associates (Cone)



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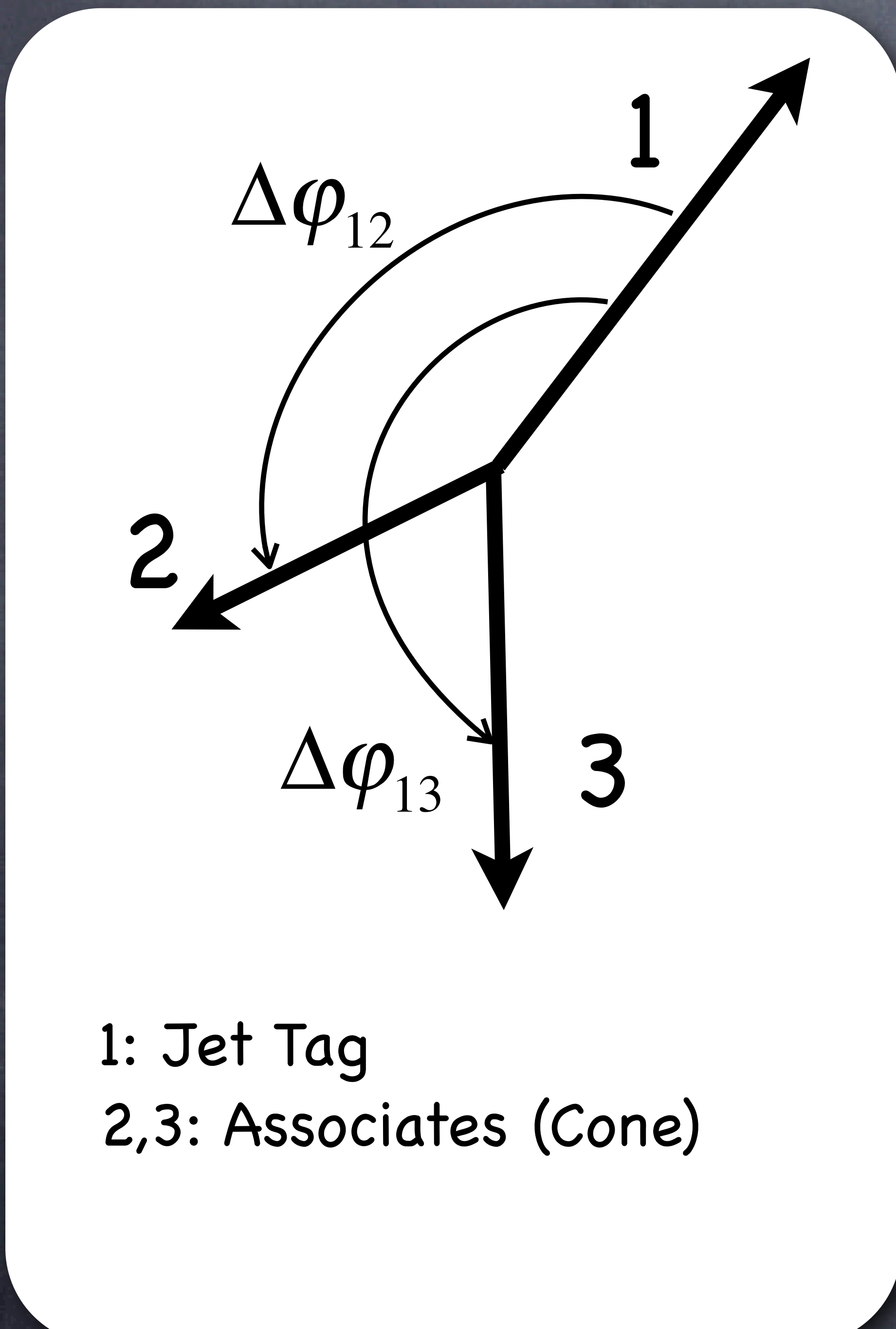

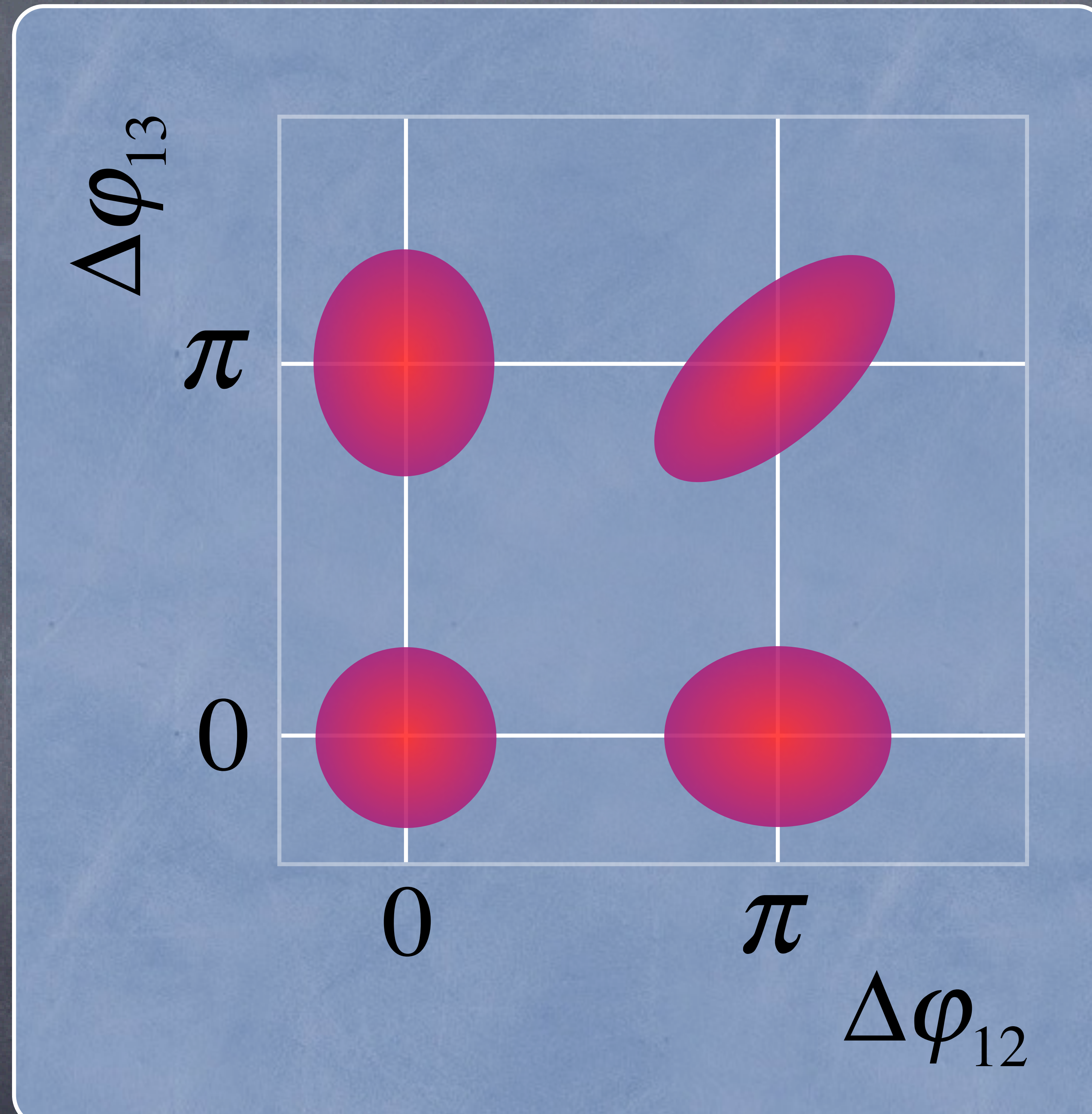

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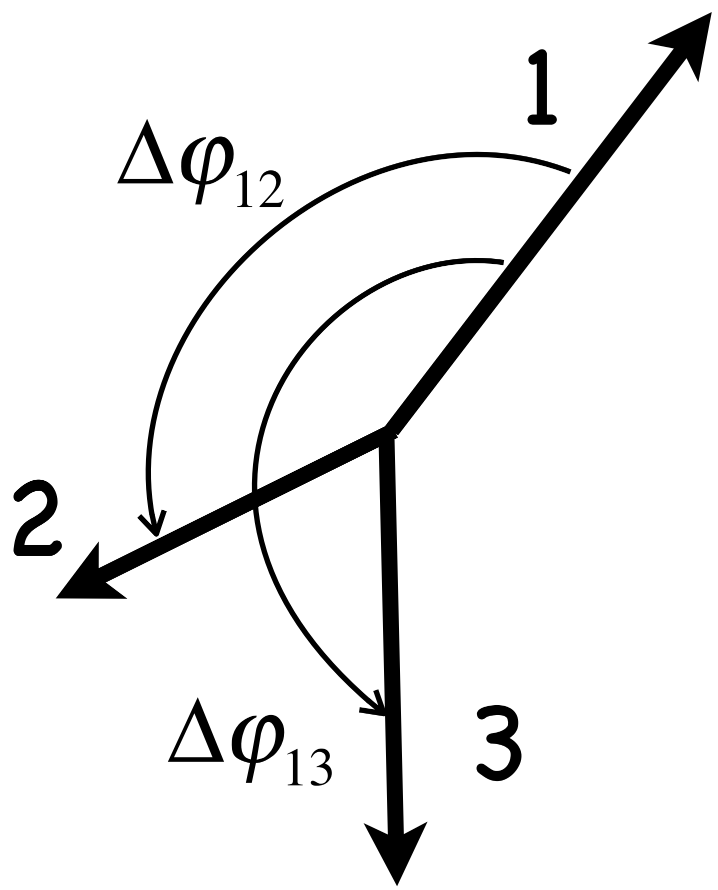

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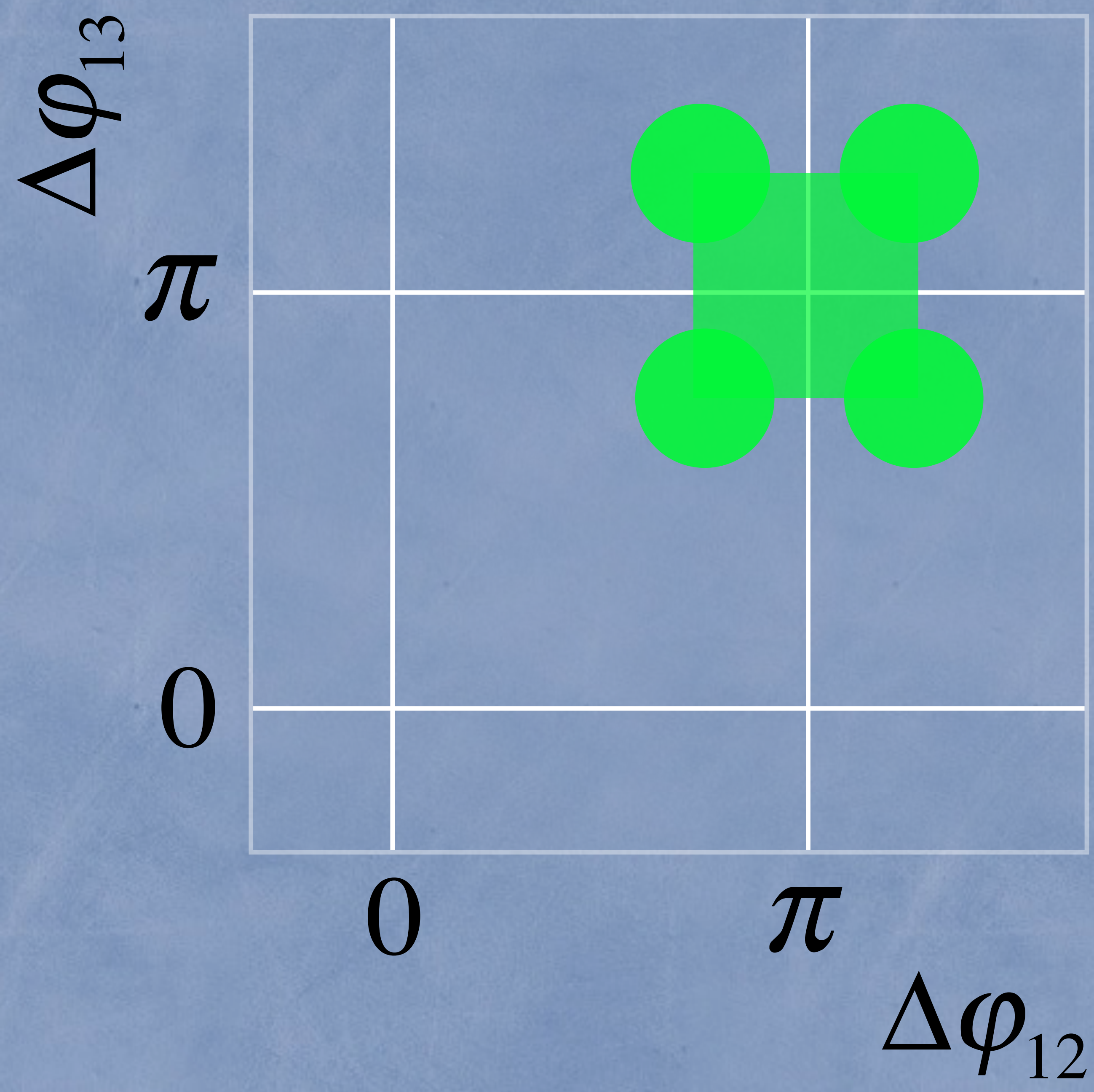


3-Particle Correlation Measurements: Searching for Conical Emission

- What is measured: **3-particle density**
- What is needed: **3-particle correlation**
  - Measure cumulants
  - Or use model to subtract "background" (ZYAM type approaches)
- Issues **(aka Why I do not like ZYAM)**
  - Remove combinatorial backgrounds
  - Collective Flow: Azimuthal & Radial
  - Momentum/Energy Conservation
  - Quantum Number Conservation
  - Resonance Decays
  - Measurement Robustness

Cumulant: Definition

Notation: Measured 1-, 2-, and 3-Particle Densities

$$\rho_1(\varphi_i) \equiv \frac{d^2N}{d\varphi_i} \qquad \rho_2(\varphi_i,\varphi_j) \equiv \frac{d^2N}{d\varphi_i d\varphi_j} \qquad \rho_3(\varphi_i,\varphi_j,\varphi_k) \equiv \frac{d^3N}{d\varphi_i d\varphi_j d\varphi_k}$$

2- and 3-Cumulants

$$\begin{aligned} C_2(\Delta\varphi_{12}) &= (2\pi)^{-1}\int d\varphi_1 d\varphi_2 \hat{\rho}_2(\varphi_1,\varphi_2)\delta(\varphi_1-\varphi_2-\Delta\varphi_{12}) \\ &= \rho_2(\Delta\varphi_{12}) - \rho_1(1)\rho_1(2) \end{aligned}$$

$$\begin{aligned} C_3(\Delta\varphi_{12},\Delta\varphi_{13}) = {} & \rho_3(\Delta\varphi_{12},\Delta\varphi_{13}) - \rho_2(\Delta\varphi_{12})\rho_1(3) - \rho_2(\Delta\varphi_{13})\rho_1(2) \\ & -\rho_2(\Delta\varphi_{13}-\Delta\varphi_{12})\rho_1(1) + 2\rho_1(1)\rho_1(2)\rho_1(3) \end{aligned}$$

Probability Cumulant

$$P_3(\Delta\varphi_{12},\Delta\varphi_{13}) = \frac{\rho_3(\Delta\varphi_{12},\Delta\varphi_{13})}{\langle N_1N_2N_3\rangle} - \frac{\rho_2(\Delta\varphi_{12})\rho_1(3)}{\langle N_1N_2\rangle\langle N_3\rangle} - \frac{\rho_2(\Delta\varphi_{13})\rho_1(2)}{\langle N_1N_3\rangle\langle N_2\rangle}$$

$$- \frac{\rho_2(\Delta\varphi_{13}-\Delta\varphi_{12})\rho_1(1)}{\langle N_2N_3\rangle\langle N_1\rangle} + 2\frac{\rho_1(1)\rho_1(2)\rho_1(3)}{\langle N_1\rangle\langle N_2\rangle\langle N_3\rangle}$$

Key Cumulant Property

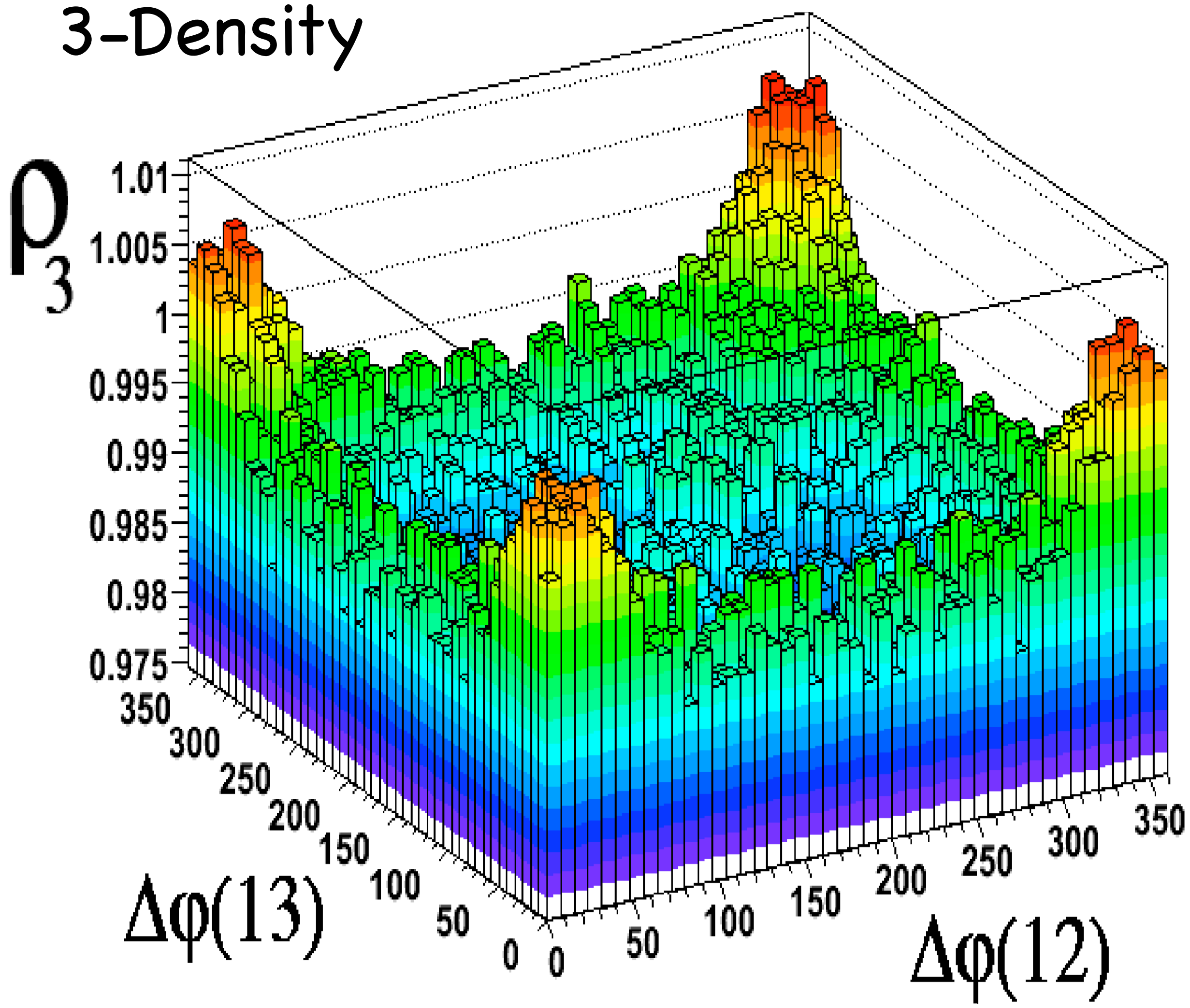
- In a system involving multiple INDEPENDENT sources (processes), the Cumulant of the whole system is equal to the sum of the cumulants of each of the sources.
- Enables to factorize the different effects contributing to the measured cumulant
  - Exception: System wide correlations e.g. Momentum conservation.

3-Cumulant:
Suppress 2-particle correlations

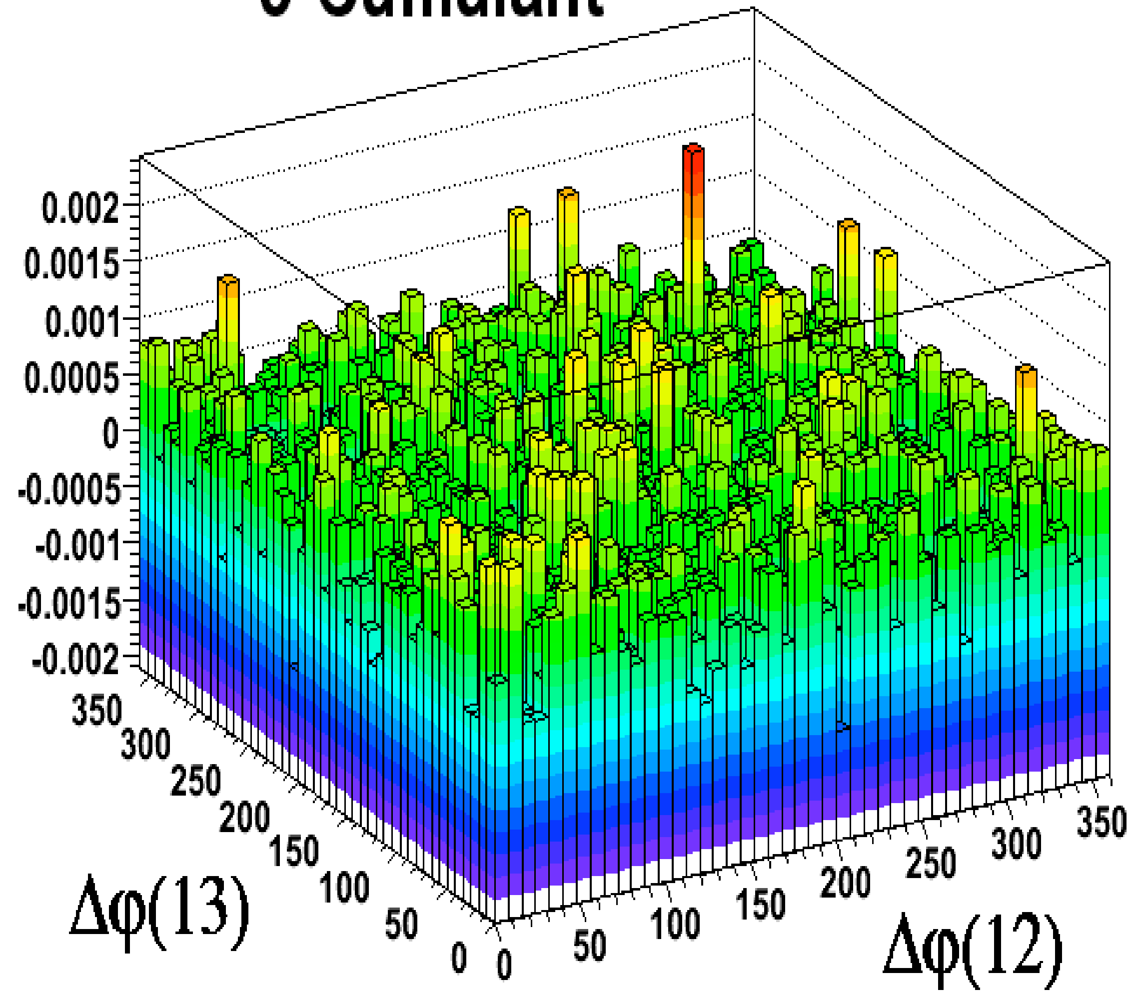
Example: Two-particle decay simulation:

Thermal Thermal Rho Spectrum $\rho \rightarrow \pi^{+} + \pi^{-}$

3-Density



3-Cumulant



Anisotropic Flow

- All particles are correlated to the reaction plane direction.
- Implies: All particles are correlated.
- Correlations exist at all orders...

Anisotropic Flow

C.P., In print PRC, **arXiv:0810.1461**

$$P_F(\varphi_i \mid \psi) = 1 + 2\sum_m v_m(i)\cos\left(m\left(\varphi_i - \psi\right)\right)$$

$$C_{2,Flow}(\Delta\varphi_{ij}) = (2\pi)^{-2}\left\langle N_i N_j \right\rangle\left(1 - d_{ij} + 2\sum_m v_m(i)v_m(j)\cos\left(m\Delta\varphi_{ij}\right)\right)$$

$$C_{3,Flow}(\Delta\varphi_{ij},\Delta\varphi_{ik}) = (2\pi)^{-3}\left\langle N_i N_j N_k \right\rangle\left\{\begin{array}{l}\Phi_3(\Delta\varphi_{ij},\Delta\varphi_{ik}) \\ +(1-f_{ijk})\Phi_2(\Delta\varphi_{ij}) + (1-f_{ikj})\Phi_2(\Delta\varphi_{ik}) + (1-f_{jki})\Phi_2(\Delta\varphi_{jk}) \\ +1 - f_{ijk} - f_{ikj} - f_{jki} + 2g_{ijk}\end{array}\right\}$$

$$d_{ij} = \frac{\langle N_i\rangle\langle N_j\rangle}{\langle N_i N_j\rangle}; \quad f_{ij} = \frac{\langle N_i N_j\rangle\langle N_k\rangle}{\langle N_i N_j N_k\rangle}; \quad g_{ij} = \frac{\langle N_i\rangle\langle N_j\rangle\langle N_k\rangle}{\langle N_i N_j N_k\rangle}$$

$$\Phi_2(\Delta\varphi_{ij}) = 2\sum_m v_p(i)v_m(j)\cos\left(p\varphi_i - m\varphi_j - n\varphi_k\right)$$

$$\Phi_3(\Delta\varphi_{ij},\Delta\varphi_{ik}) = 2\sum_{p,m,n} v_p(i)v_m(j)v_n(k)\left[\begin{array}{l}\delta_{p,m+n}\cos\left(p\varphi_i - m\varphi_j - n\varphi_k\right) \\ +\delta_{m,p+n}\cos\left(-p\varphi_i + m\varphi_j - n\varphi_k\right) \\ +\delta_{n,m+k}\cos\left(-p\varphi_i - m\varphi_j + n\varphi_k\right)\end{array}\right]$$

Anisotropic Flow

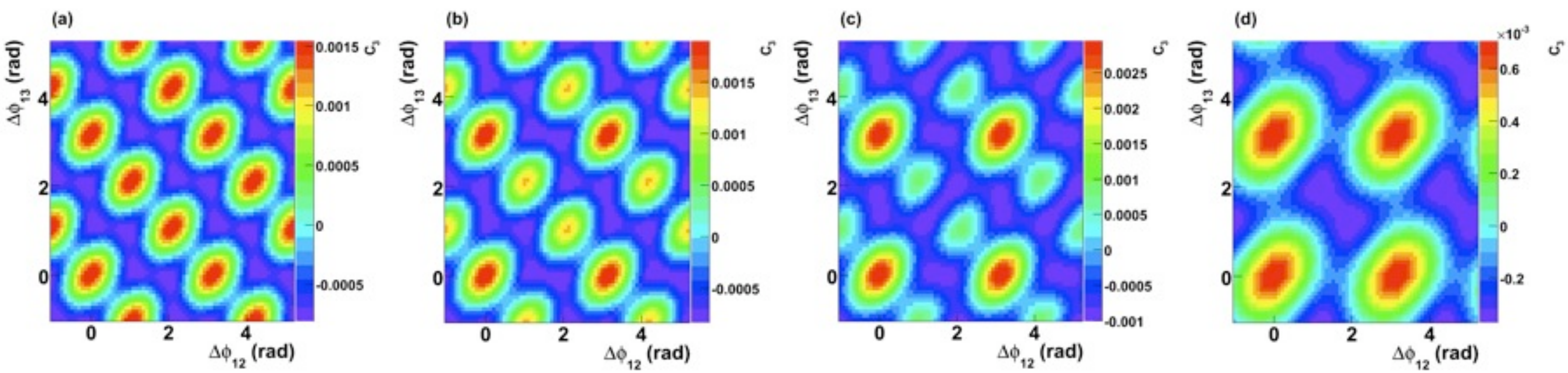
C.P., In print PRC, **arXiv:0810.1461**

$$d_{ij}=\frac{\langle N_i\rangle\langle N_j\rangle}{\langle N_iN_j\rangle};\quad f_{ij}=\frac{\langle N_iN_j\rangle\langle N_k\rangle}{\langle N_iN_jN_k\rangle};\quad g_{ij}=\frac{\langle N_i\rangle\langle N_j\rangle\langle N_k\rangle}{\langle N_iN_jN_k\rangle}$$

$$\Phi_2(\Delta\varphi_{ij})=2\sum_m v_p(i)v_m(j)\cos\left(p\varphi_i-m\varphi_j-n\varphi_k\right)$$

$$\Phi_3(\Delta\varphi_{ij},\Delta\varphi_{ik})=2\sum_{p,m,n} v_p(i)v_m(j)v_n(k)\begin{bmatrix}\delta_{p,m+n}\cos\left(p\varphi_i-m\varphi_j-n\varphi_k\right)\\+\delta_{m,p+n}\cos\left(-p\varphi_i+m\varphi_j-n\varphi_k\right)\\+\delta_{n,m+k}\cos\left(-p\varphi_i-m\varphi_j+n\varphi_k\right)\end{bmatrix}$$

3-Cumulant



$d_{ij}=f_{ij}=g_{ij}=1$

$v_4>0$

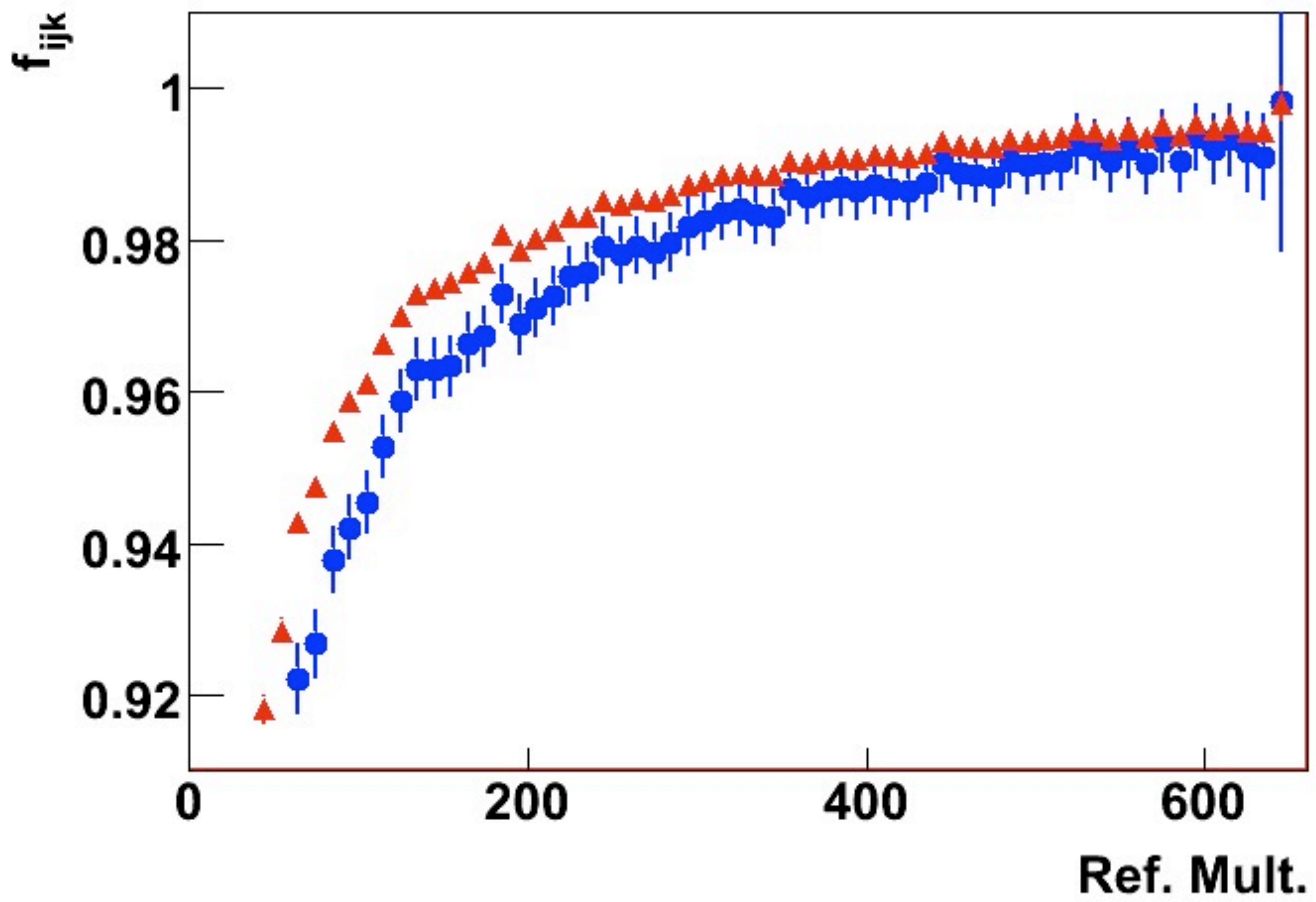
$$\frac{v_2v_2v_4}{\left(1-f_{ij}\right)v_2v_2}=0.5$$

$$\frac{v_2v_2v_4}{\left(1-f_{ij}\right)v_2v_2}=2$$

$f_{ij}<1$

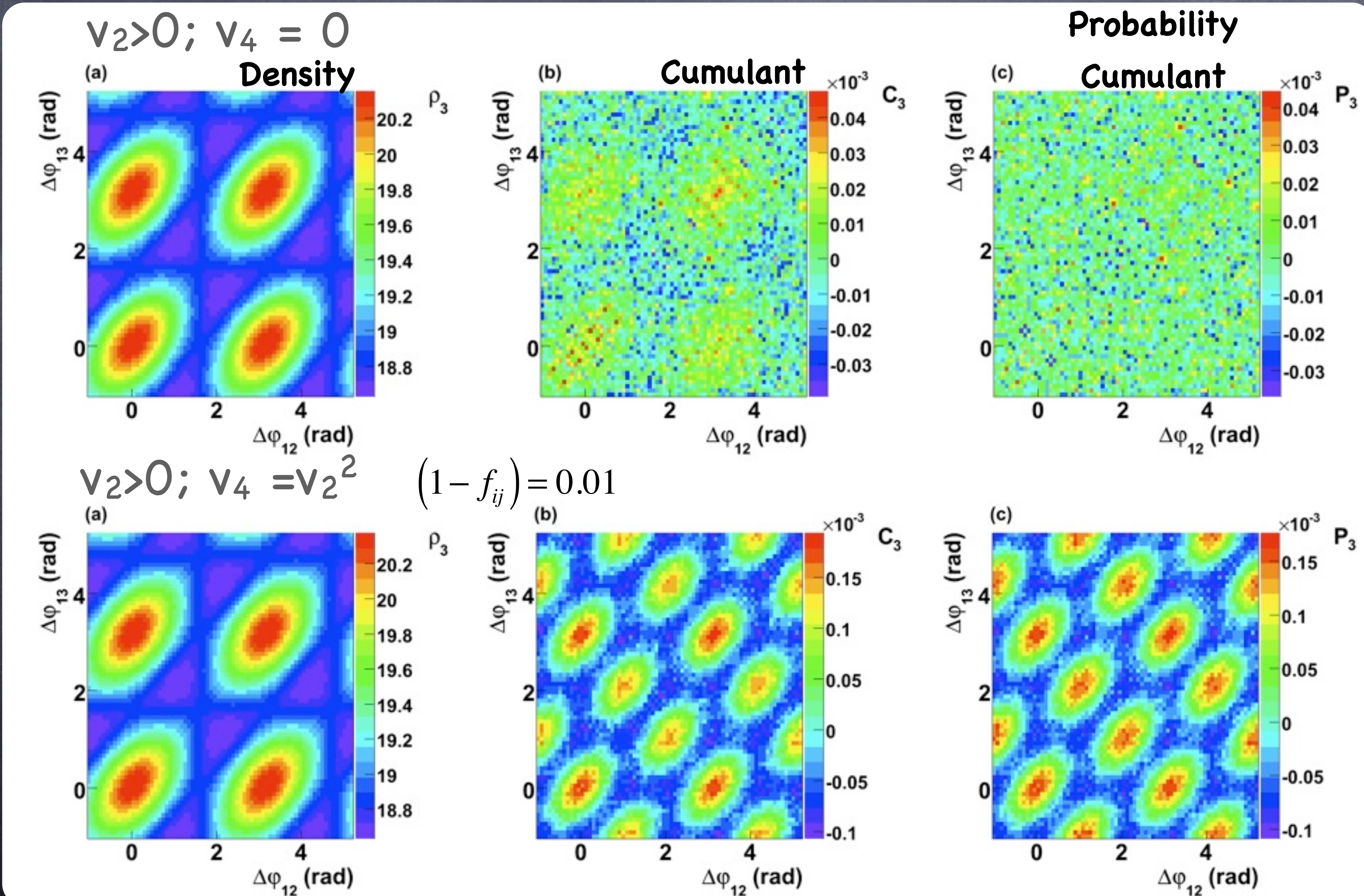
$v_4=0$

Au+Au 200 GeV 3-20 GeV, 1-2 GeV

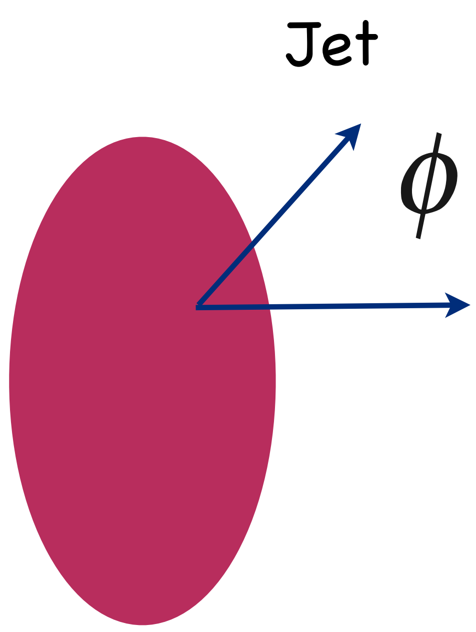


STAR Preliminary

Flow - Simulations ◎ C_3 vs P_3



Jet - Flow Cross Term - A toy Model



Particle angle

Jet axis

Jet Profile:

$$P_{Jet}(\varphi_i \mid \phi) = G(\varphi_i - \phi; \sigma_i) = \frac{1}{\sqrt{2\pi}\sigma_i}\exp\left(-\frac{(\varphi_i-\phi)^2}{2\sigma_i}\right)$$

Jet width

Reaction Plane

Jet Flow:

$$P_{Jet-Axis}(\phi \mid \psi) = 1 + 2\sum_n v_n(jet)\cos(n(\phi-\psi))$$

Background Flow:

$$P_{BCKG}(\varphi_k \mid \psi) = 1 + 2\sum_n v_n(bckg)\cos(n(\varphi_k-\psi))$$

3-Cumulant:

Avg. Jet/event

Avg. Associates/jet

Avg. Bckg/jet

$$C_3(\varphi_i,\varphi_j,\varphi_k)_{FJ} = 2(2\pi)^{-1}\langle J\rangle\langle A_iA_j\rangle\langle B_k\rangle$$

$$\times\sum_n v_n(jet)v_n(bckg)\exp\left(-\frac{n^2\sigma_i^2\sigma_j^2}{2\sigma_{ij}^2}\right)\exp\left(-\frac{\Delta\varphi_{ij}}{2\sigma_{ij}^2}\right)\cos\left(n\left(\varphi_k-\alpha_i\varphi_i-\alpha_j\varphi_j\right)\right)$$

$$\sigma_{ij}^2 = \sigma_i^2 + \sigma_j^2 \qquad \alpha_i = \frac{\sigma_j^2}{\sigma_i^2+\sigma_j^2}$$

Jet - Flow Cross Term - A toy Model

$$C_3(\varphi_i,\varphi_j,\varphi_k)_{FJ} = 2(2\pi)^{-1}\langle J\rangle\left\langle A_iA_j\right\rangle\left\langle B_k\right\rangle$$

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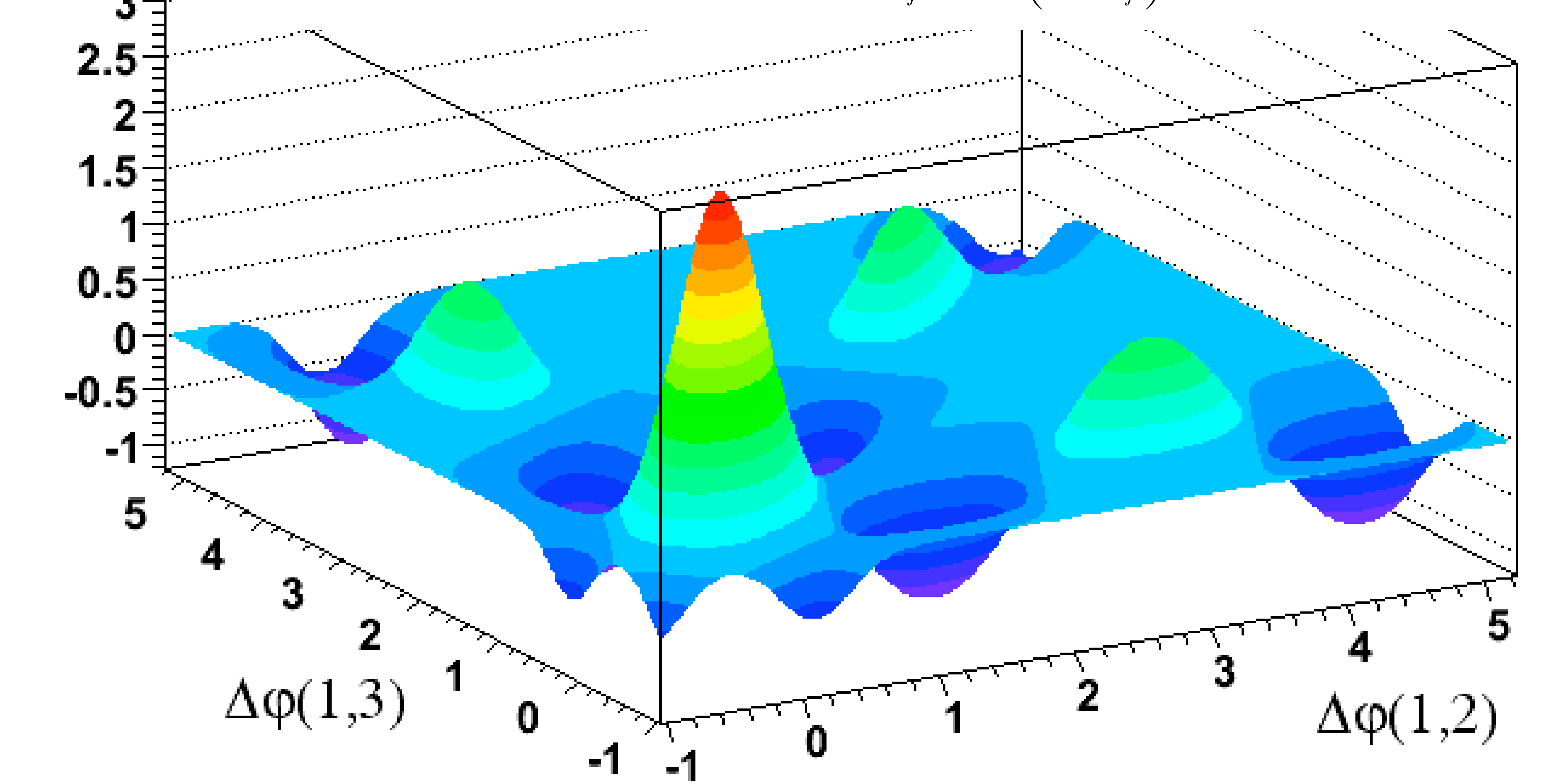


Momentum/Energy Conservation

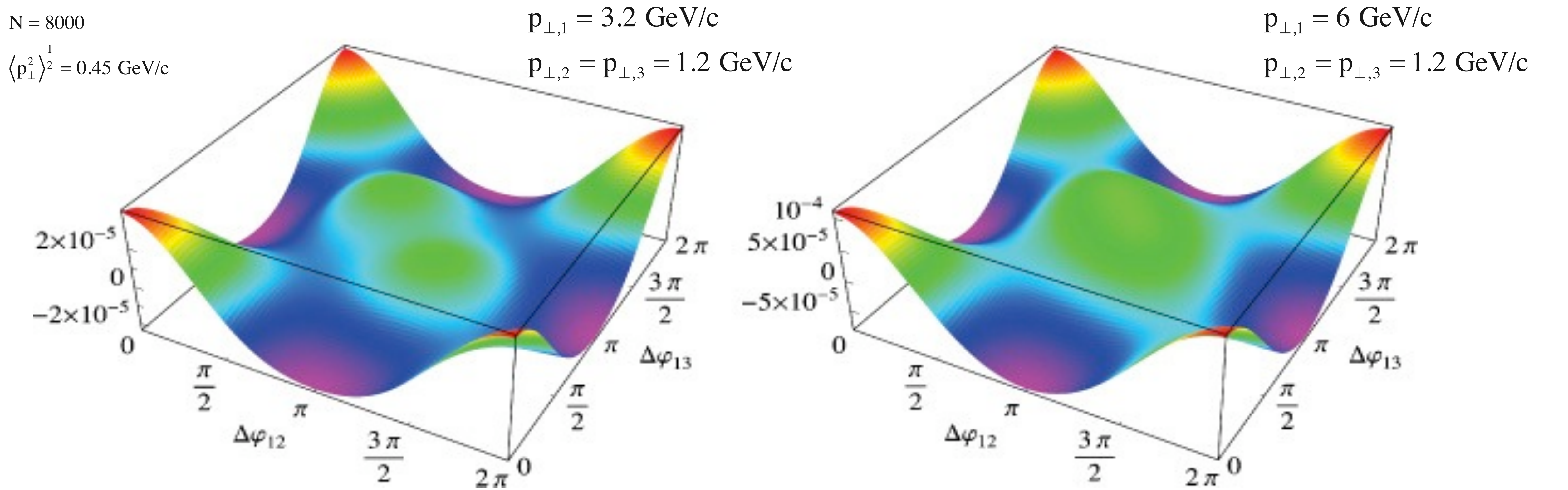
- Momentum/Energy Conservation involves all particles.
- Implies: All particles are correlated.
- Correlations exist at all orders...

Momentum Conservation Induced Correlations

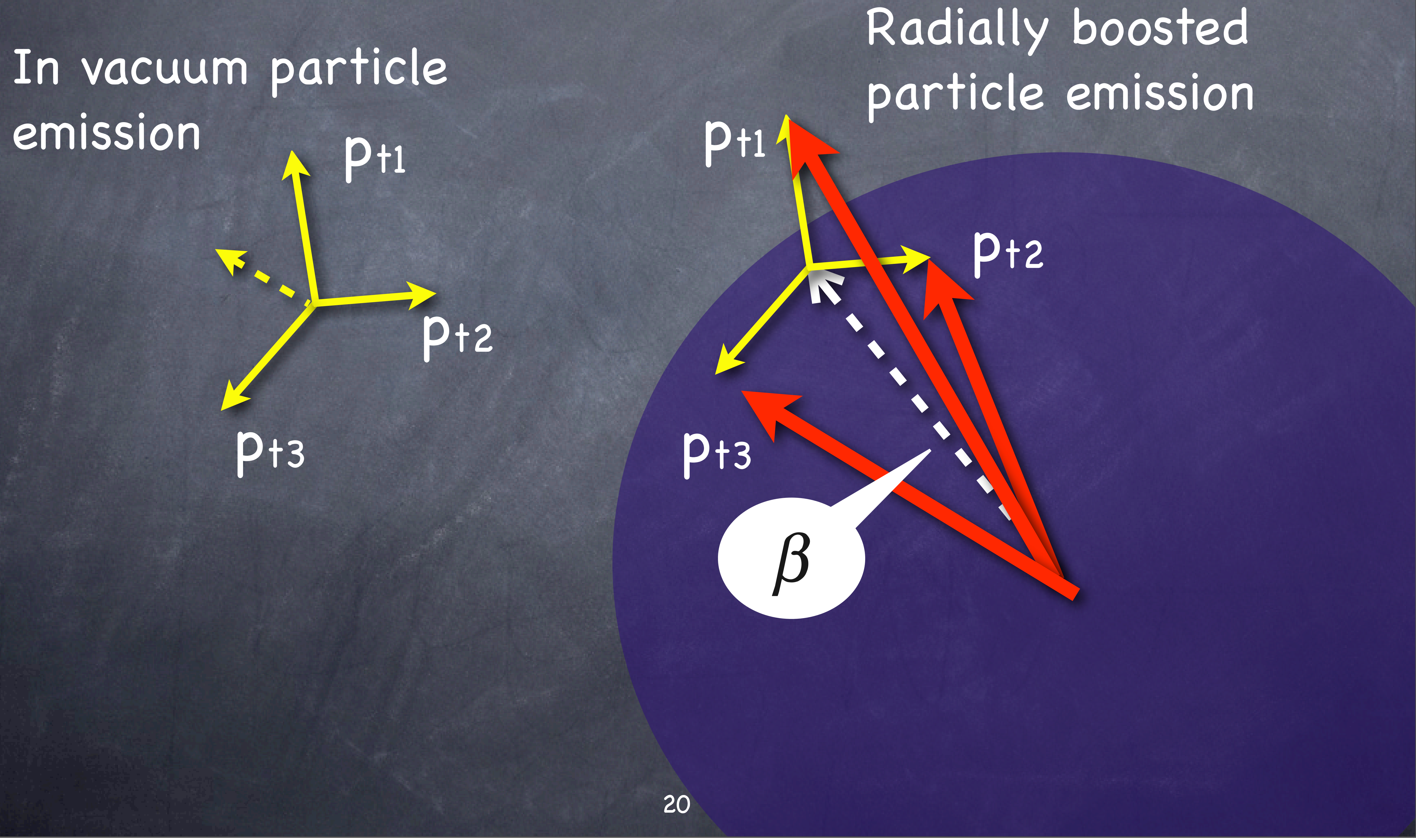
- N. Borghini, PRC 75, 21904(R) (2007).
- 3-cumulant scales as $1/N^2$.
- Assumes single-particle distribution is isotropic
- Also see Zbigniew Chajecki and Mike Lisa, arXiv:0807.3569

$$f_c(\mathbf{p}_{T1}, \mathbf{p}_{T2}) = -\frac{2\,\mathbf{p}_{T1}\cdot\mathbf{p}_{T2}}{N\langle \mathbf{p}_T^2\rangle}, \tag{1}$$

$$\begin{aligned} f_c(\mathbf{p}_{T1}, \mathbf{p}_{T2}, \mathbf{p}_{T3}) = &-\frac{2}{N^2\langle \mathbf{p}_T^2\rangle}(\mathbf{p}_{T1}\cdot\mathbf{p}_{T2} + \mathbf{p}_{T1}\cdot\mathbf{p}_{T3} \\ &+ \mathbf{p}_{T2}\cdot\mathbf{p}_{T3}) + \frac{4}{N^2\langle \mathbf{p}_T^2\rangle^2}[(\mathbf{p}_{T1}\cdot\mathbf{p}_{T2}) \\ &\times(\mathbf{p}_{T1}\cdot\mathbf{p}_{T3}) + (\mathbf{p}_{T1}\cdot\mathbf{p}_{T2})(\mathbf{p}_{T2}\cdot\mathbf{p}_{T3}) \\ &+ (\mathbf{p}_{T1}\cdot\mathbf{p}_{T3})(\mathbf{p}_{T2}\cdot\mathbf{p}_{T3})], \end{aligned} \tag{2}$$



Radial Flow Induced Correlations



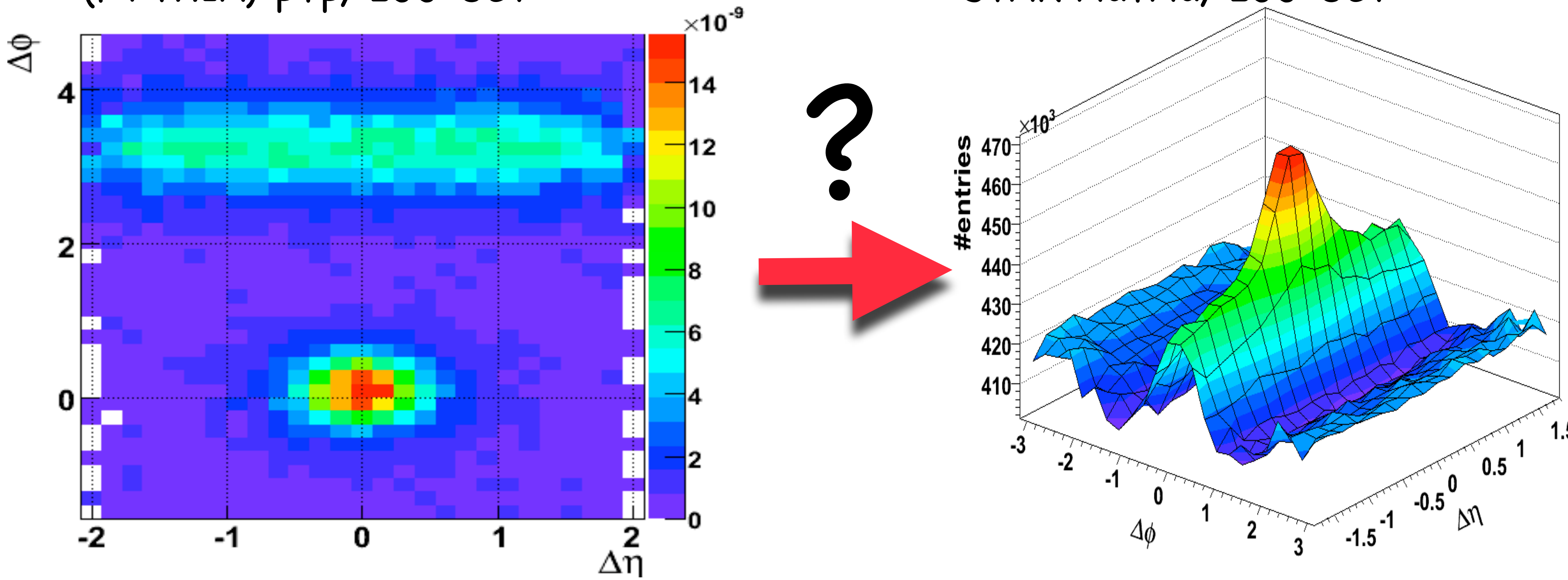
Study of Radial Flow Effects with PYTHIA

C.P., S. Gavin, S. Voloshin, Nucl. Phys. A802, 107 (2008).

- Motivation: Can the ridge found in Au+Au $\Delta\eta$ vs $\Delta\phi$ correlations be due to radial flow?
- Use PYTHIA p+p events (200 GeV) with radial boost to simulate the effect of radial flow.
- Particles emitted by one p+p interaction are all boosted in the same radial direction.

(PYTHIA) p+p, 200 GeV

STAR Au+Au, 200 GeV



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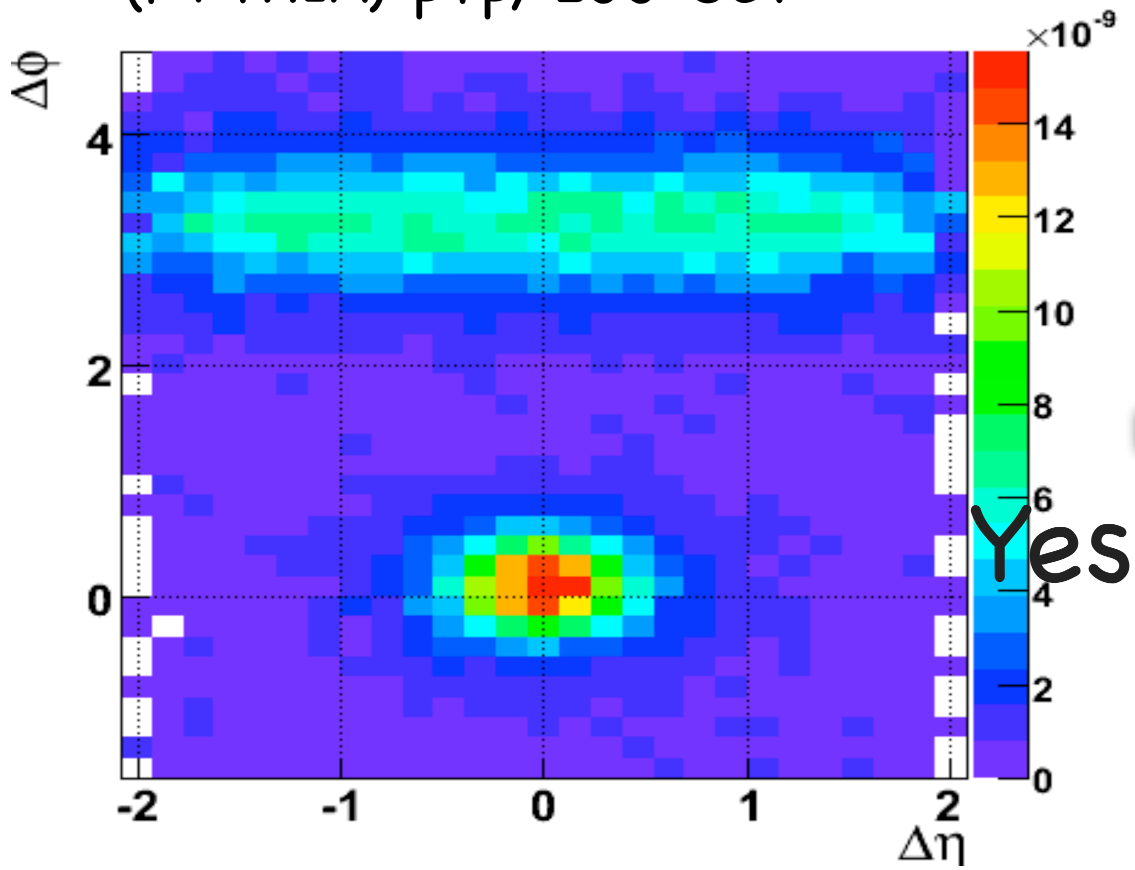
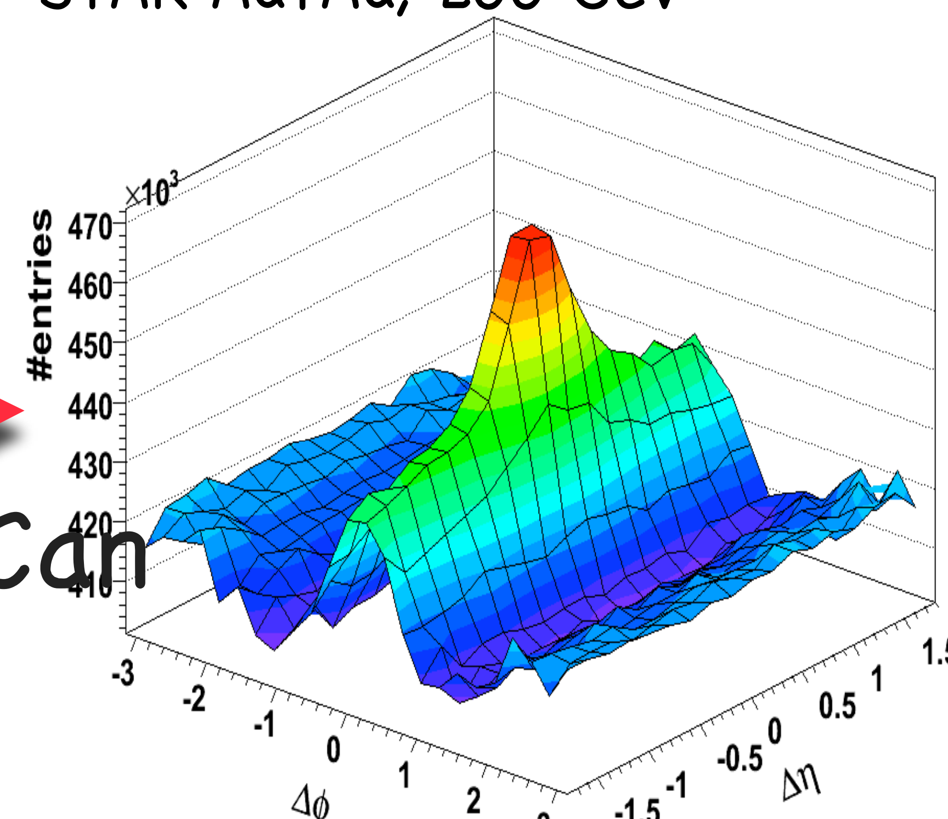


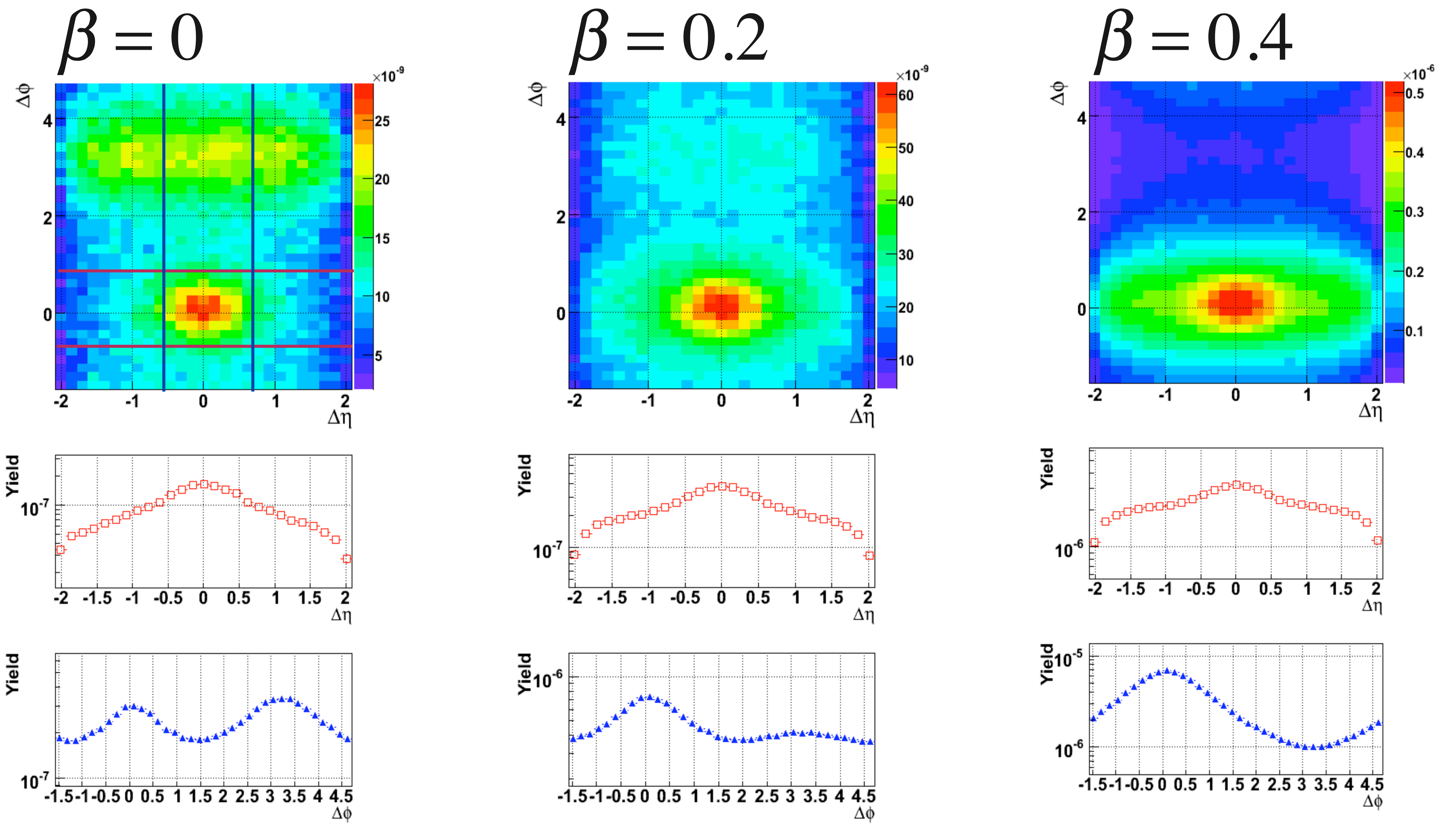
?

Yes We Can

STAR Au+Au, 200 GeV

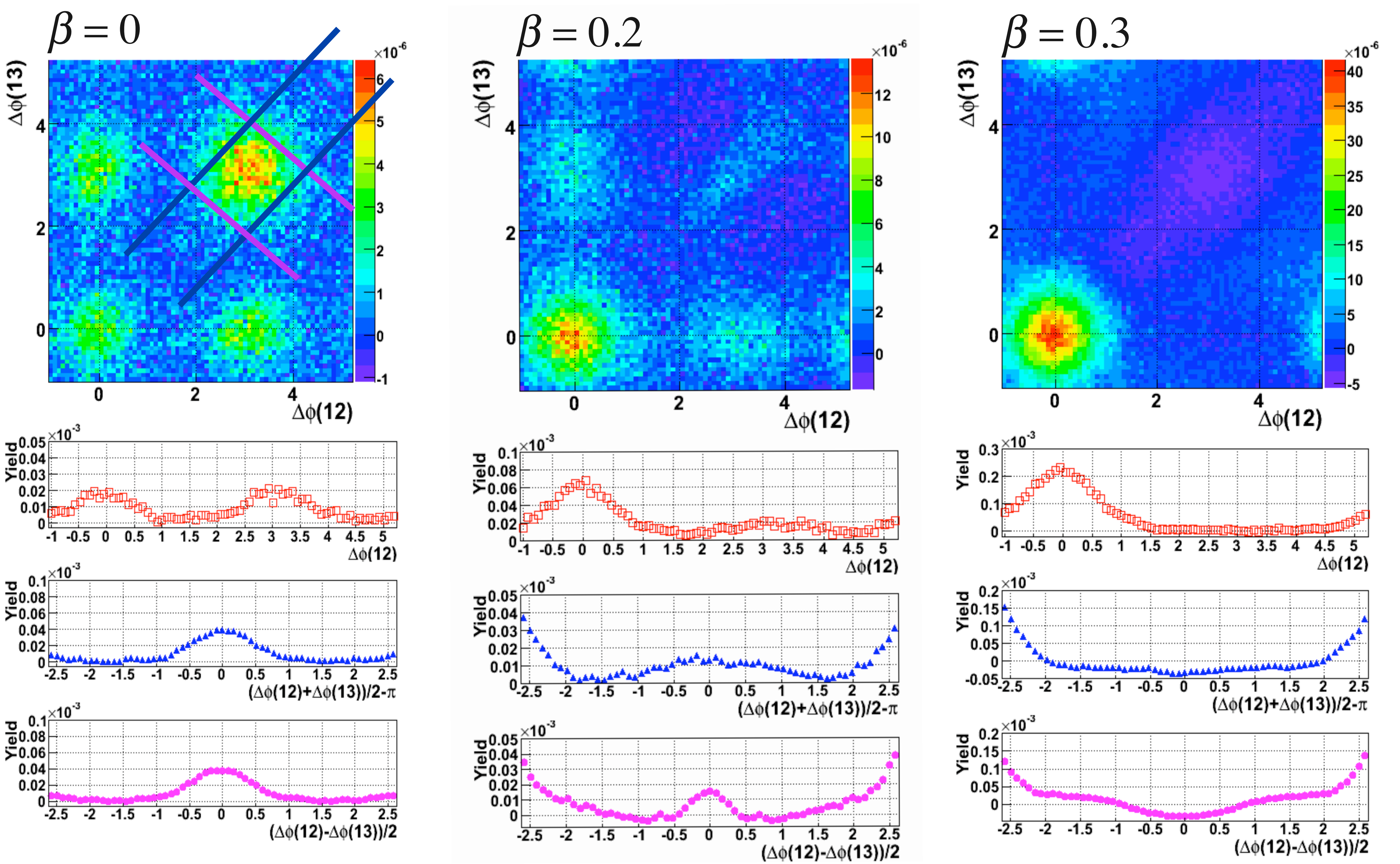


PYTHIA p+p @ sqrt(s)=200 GeV; 3<p_t<20 && 0.2<p_t<1



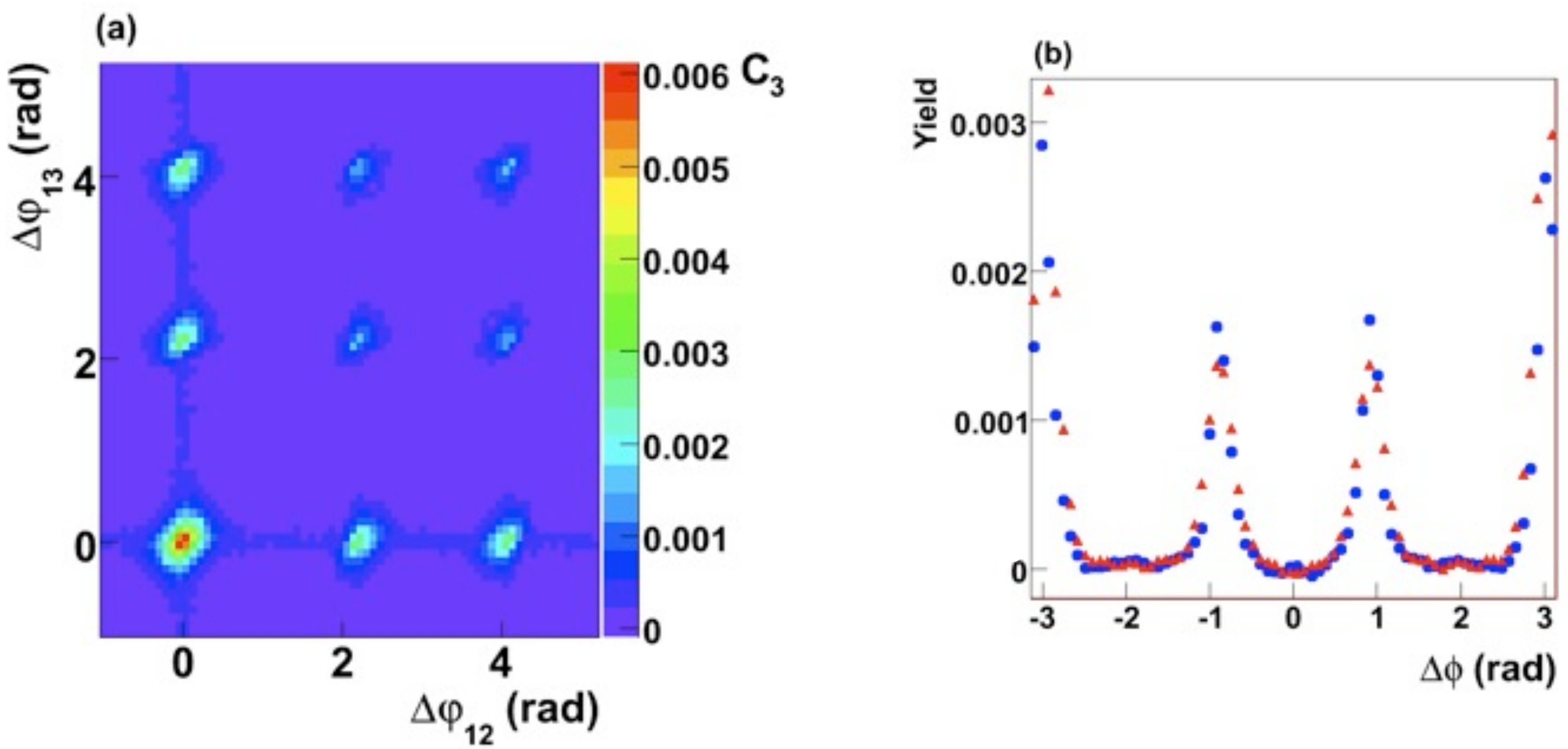
So..., what about 3-correlations??

PYTHIA p+p @ sqrt(s)=200 GeV; $3<p_t<20$ && $0.2<p_t<1$



Radial flow alters 3-cumulant

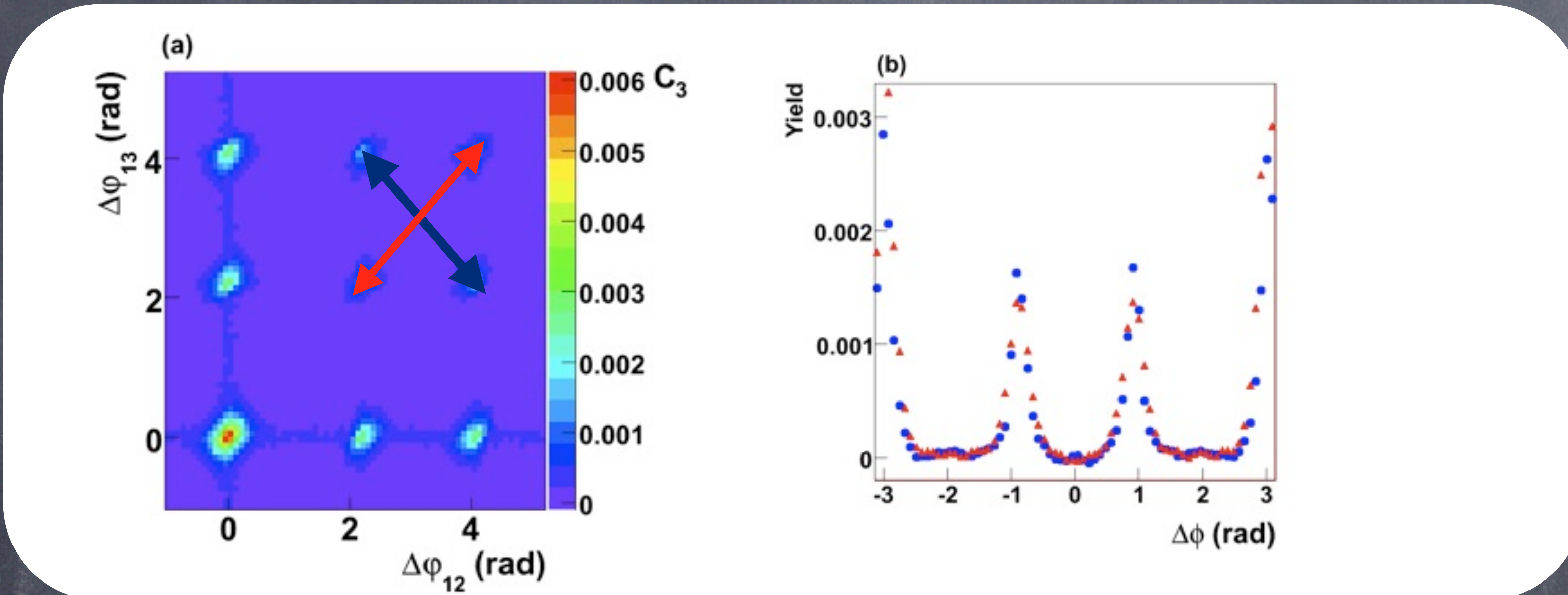
Cone Emission Simulation



Simulation: Average Multiplicities

- Particle 1 (High pt):
  - Background: 1 part/evt
  - Trigger (Jet tag): 1 part/event
- Particle 2 (Low pt):
  - Background 100 part/evt
  - Cone associates: 2 part event

Cone Emission Simulation

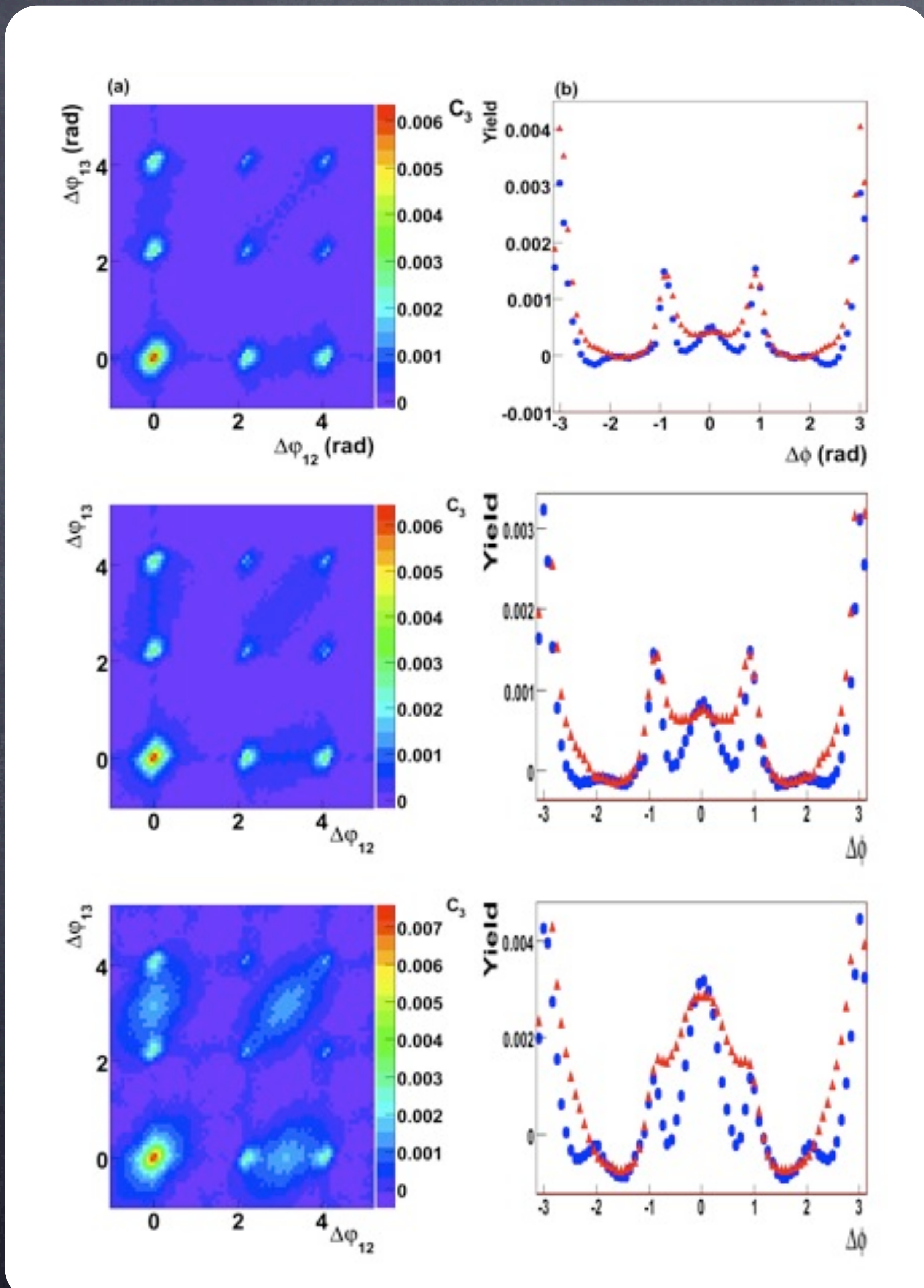


Simulation: Average Multiplicities

- Particle 1 (High pt):
  - Background: 1 part/evt
  - Trigger (Jet tag): 1 part/event
- Particle 2 (Low pt):
  - Background 100 part/evt
  - Cone associates: 2 part event

Simulation: Jet + Cone + Flow

but no jet-flow



Low pt signal/bckg = 1/100
High pt signal/bckg = 1
$v_2 = 0.1$, $v_4 = v_2^2$

High pt signal/bckg = 1/2

High pt signal/bckg = 1/4

Comments (1)

- Combinatorial background is best removed using a cumulant method: no model or physics assumptions.
- v_2^2 flow is suppressed in C_3 and zero in P_3
- Its amplitude is measurable as f_{ijk} coefficients. No ZYAM needed.
- $\langle v_2 v_2 v_4 \rangle$ is irreducible. Note: $\langle v_2 v_2 v_4 \rangle \neq \langle v_2 \rangle \langle v_2 \rangle \langle v_4 \rangle$
- No simple model (currently) for momentum conservation effects
- No estimate for 3-particle decays
- Radial Flow Effects may be large

Comments (2)

- Cone Signal clearly visible for Poisson background even in the presence of (strong) flow.
- Cone Signal visible for non-Poisson background with moderate background and flow.
- Signal difficult to extract for large background & flow.
- Approximate sensitivity:

$$\frac{\langle N_1 N_2 N_3 \rangle_{\text{signal}}}{\langle N_1 N_2 N_3 \rangle_{\text{bckg}}} \geq \quad \sim 10^{-1} v_2{}^4$$

STAR Data, Run 4
Cumulant Analysis

QM06, 08

Au + Au @ 200 GeV vs Centrality

Jet tag (Trigger): $3 < p_t < 20$ GeV

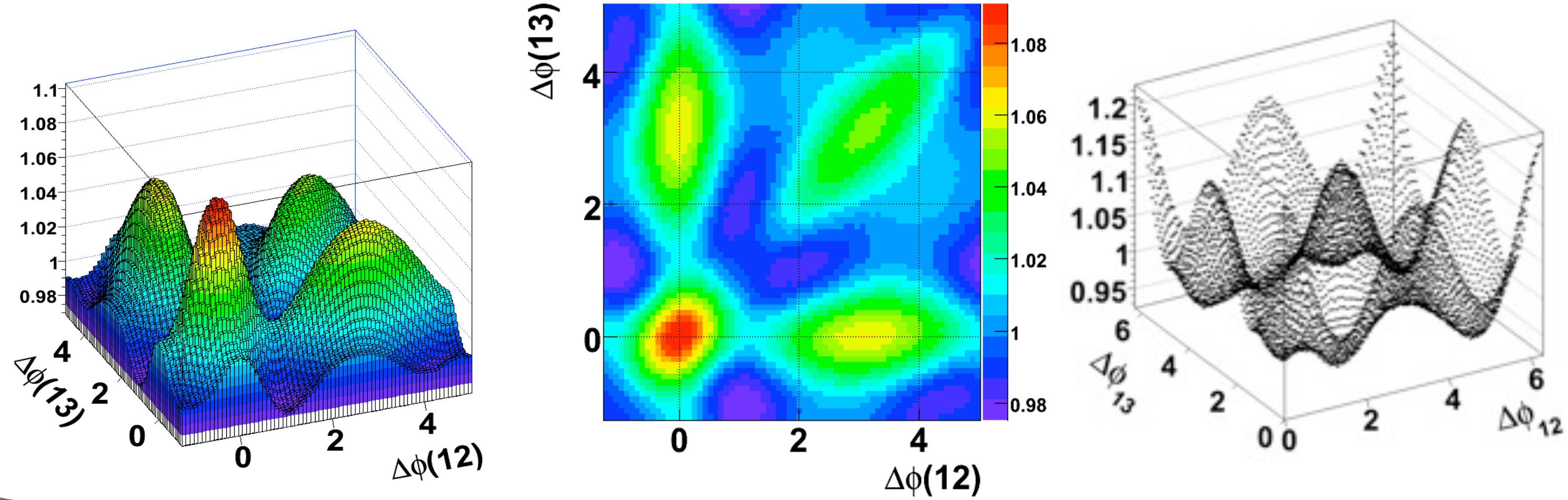
Associates (3 ranges examined)

$1 < p_t < 2$ GeV

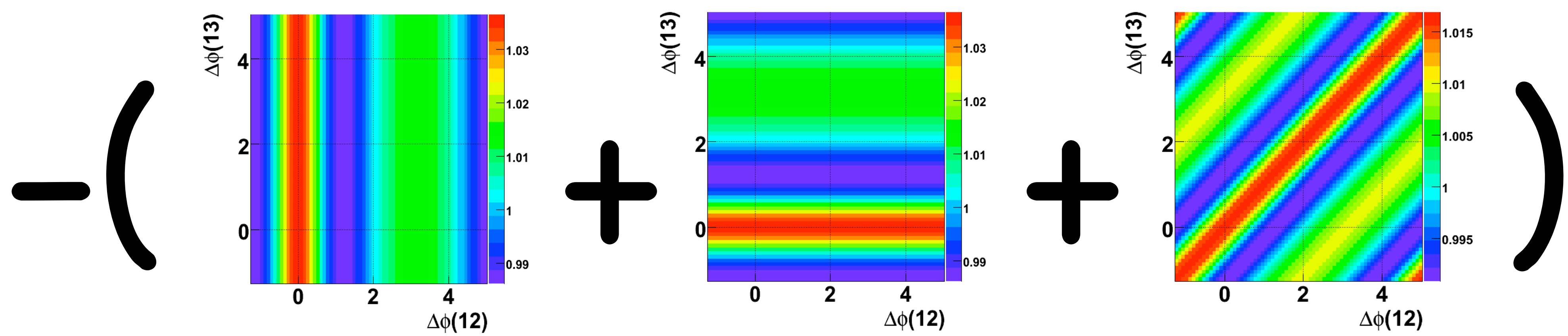
$2 < p_t < 3$ GeV

All particles $|eta| < 1$

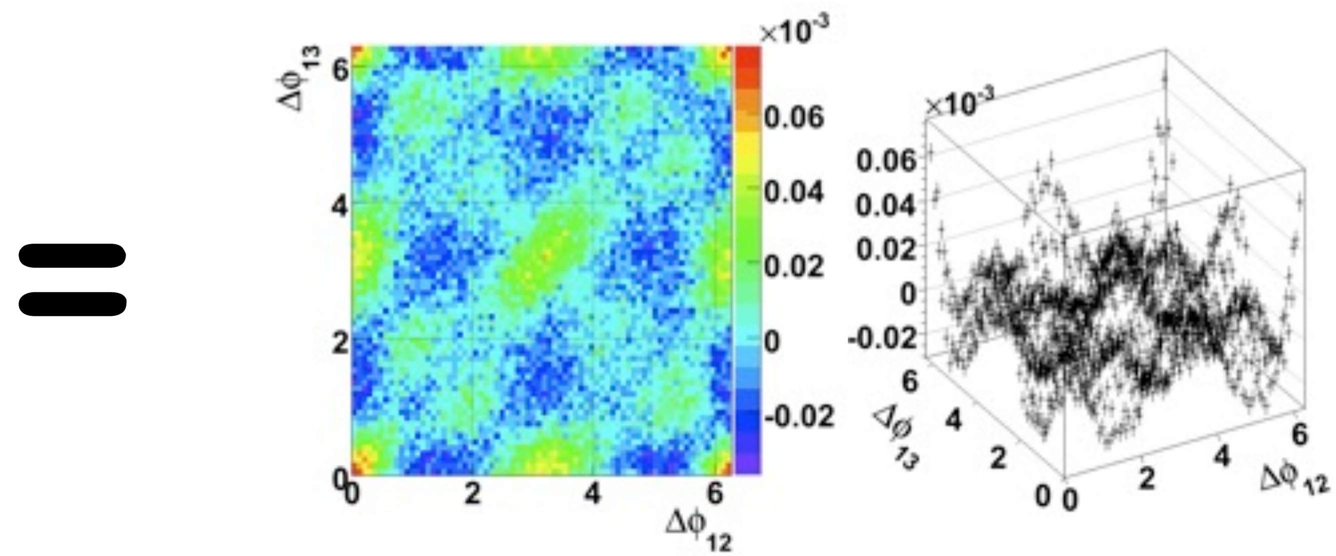
3-Particle Density
(3 views)



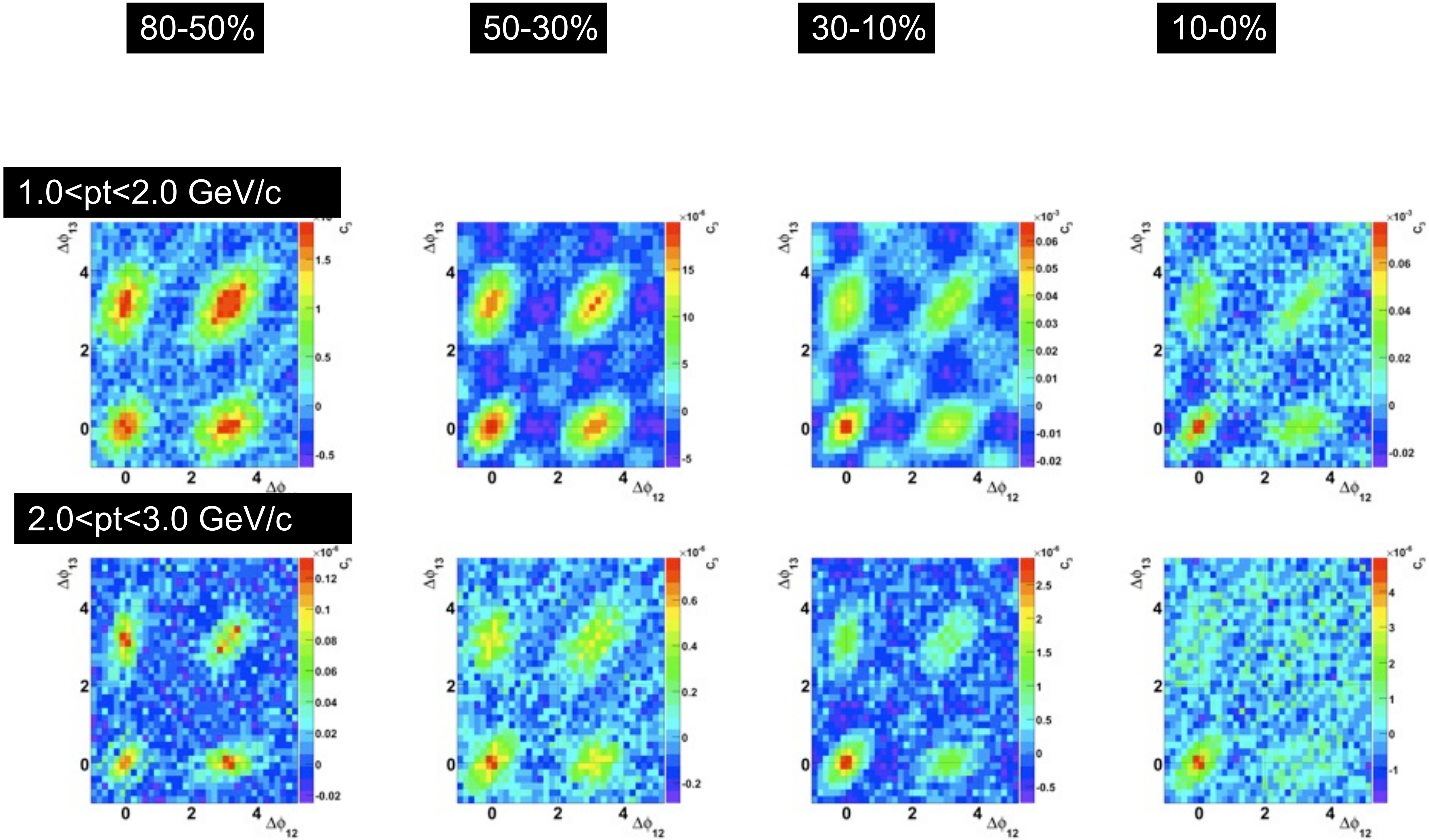
Combinatorial
Terms



3-Cumulant
(2 views)



STAR Preliminary



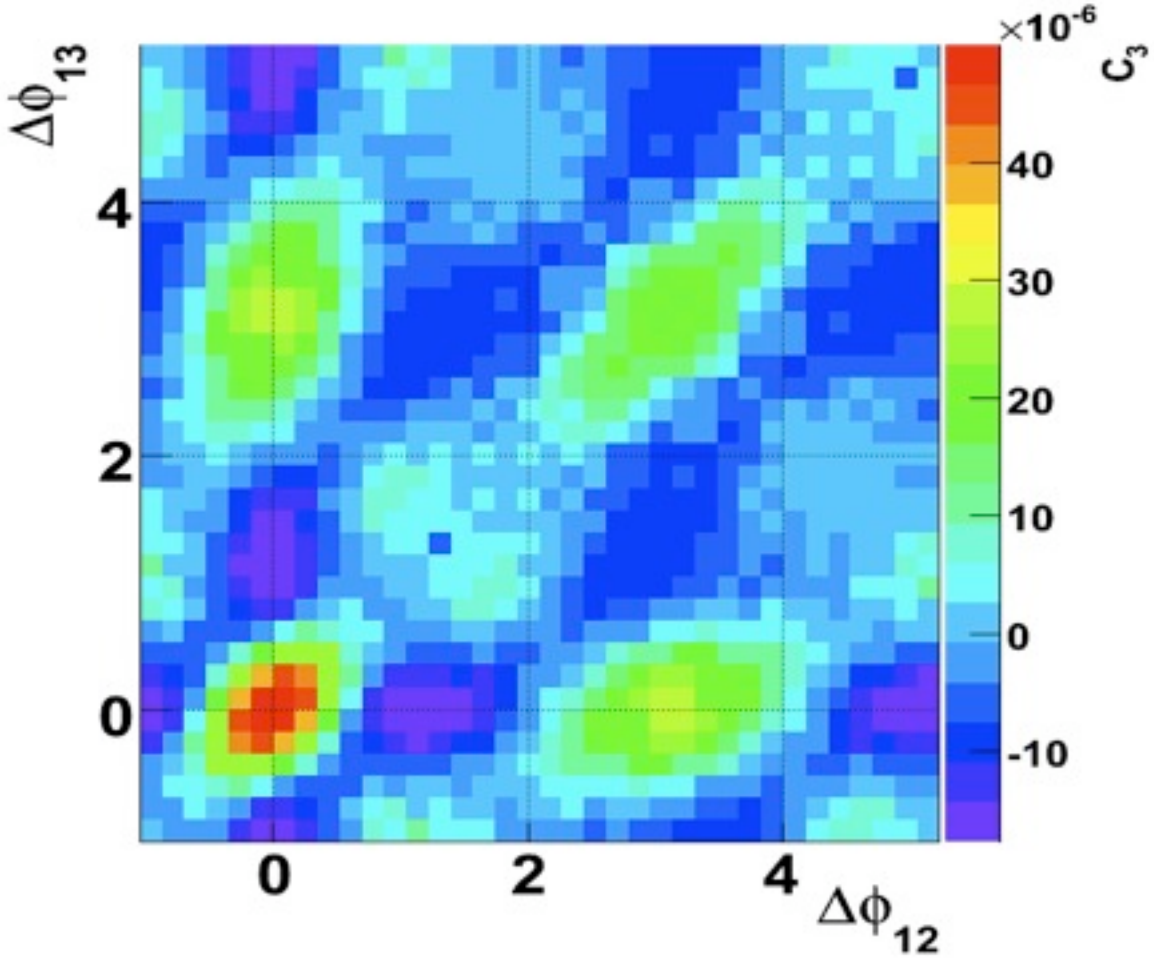
STAR Preliminary

Min-bias trigger

Central Trigger

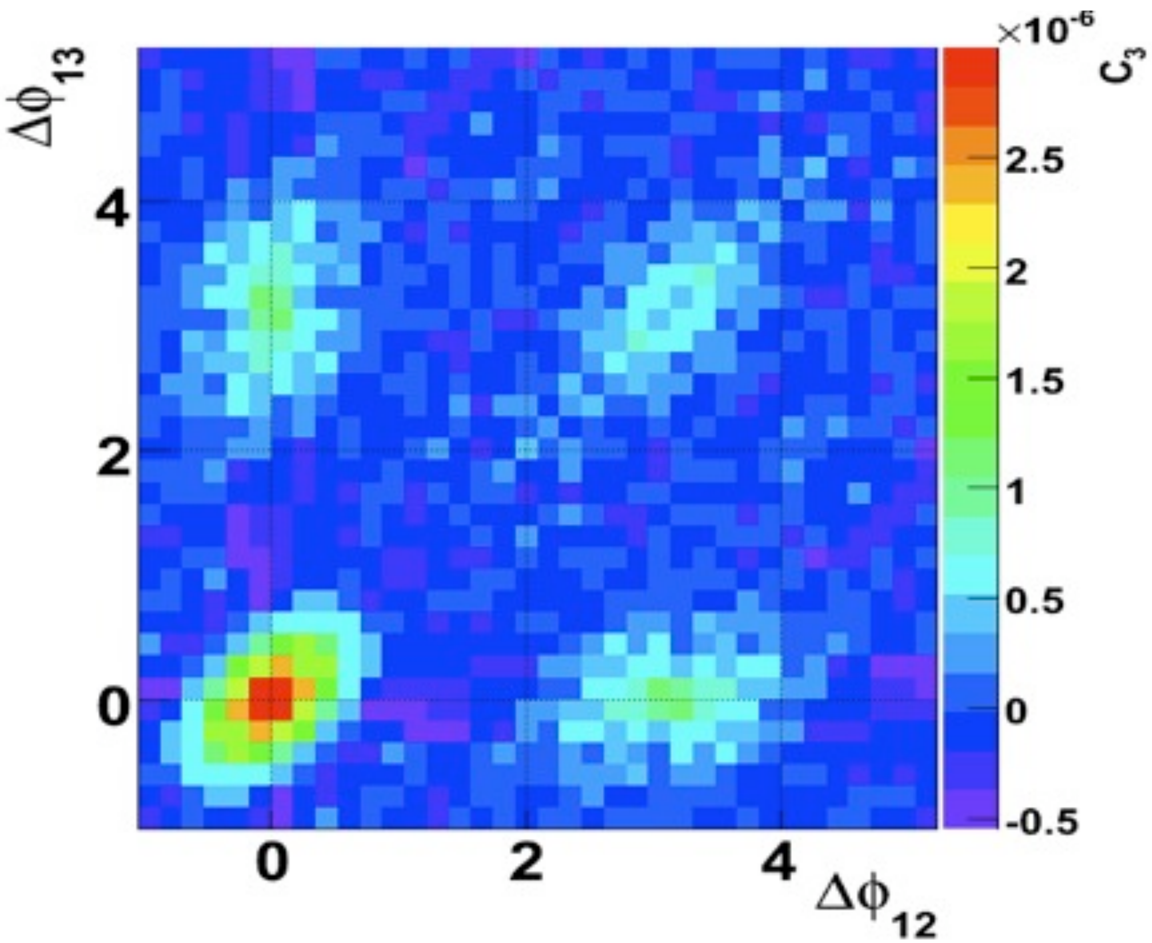
$p_{t1} > 3$ GeV/c

$1 < p_{t2,3} < 2$ GeV/c



$p_{t1} > 3$ GeV/c

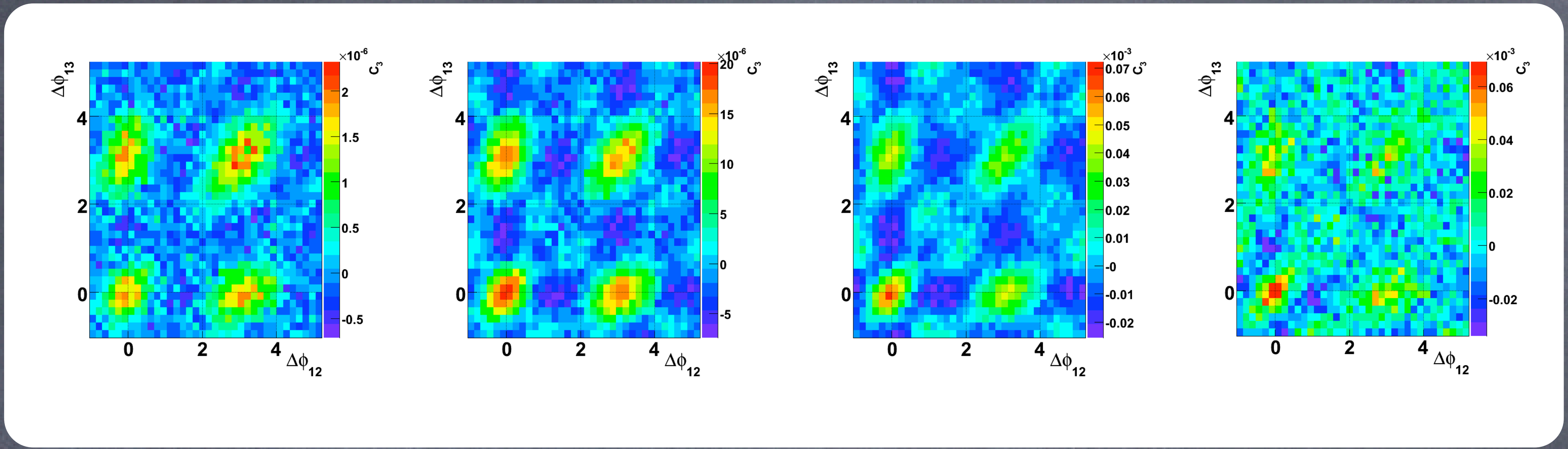
$2 < p_{t2,3} < 3$ GeV/c



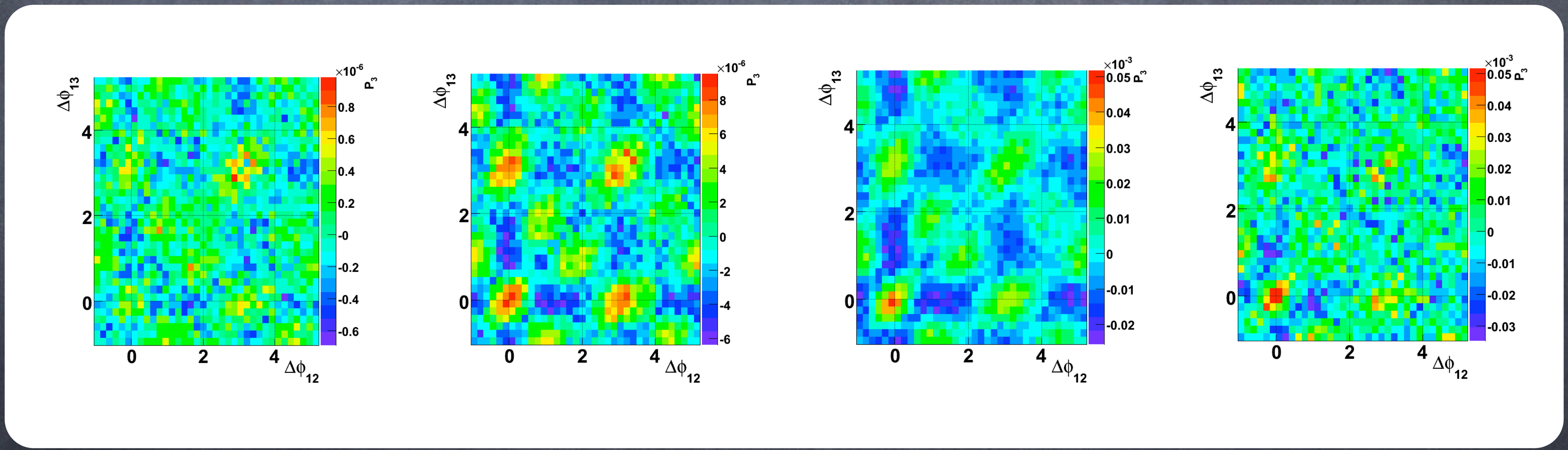
STAR Preliminary

Cumulant vs Probability Cumulant
Trigger: 3 - 20 GeV,   Associate: 1 - 2 GeV

C_3



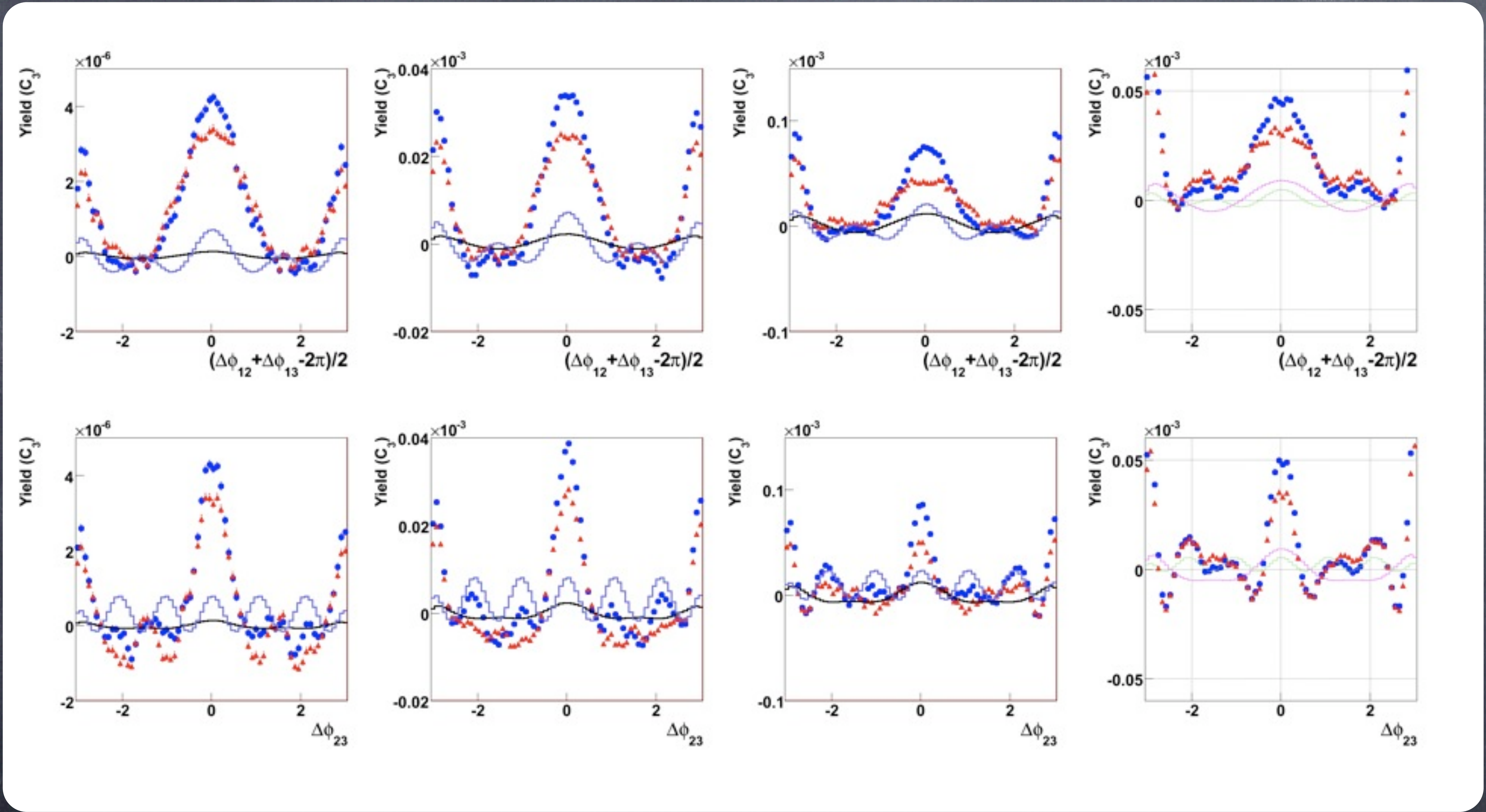
P_3



80-50% **50-30%** **30-10%** **10-0%**

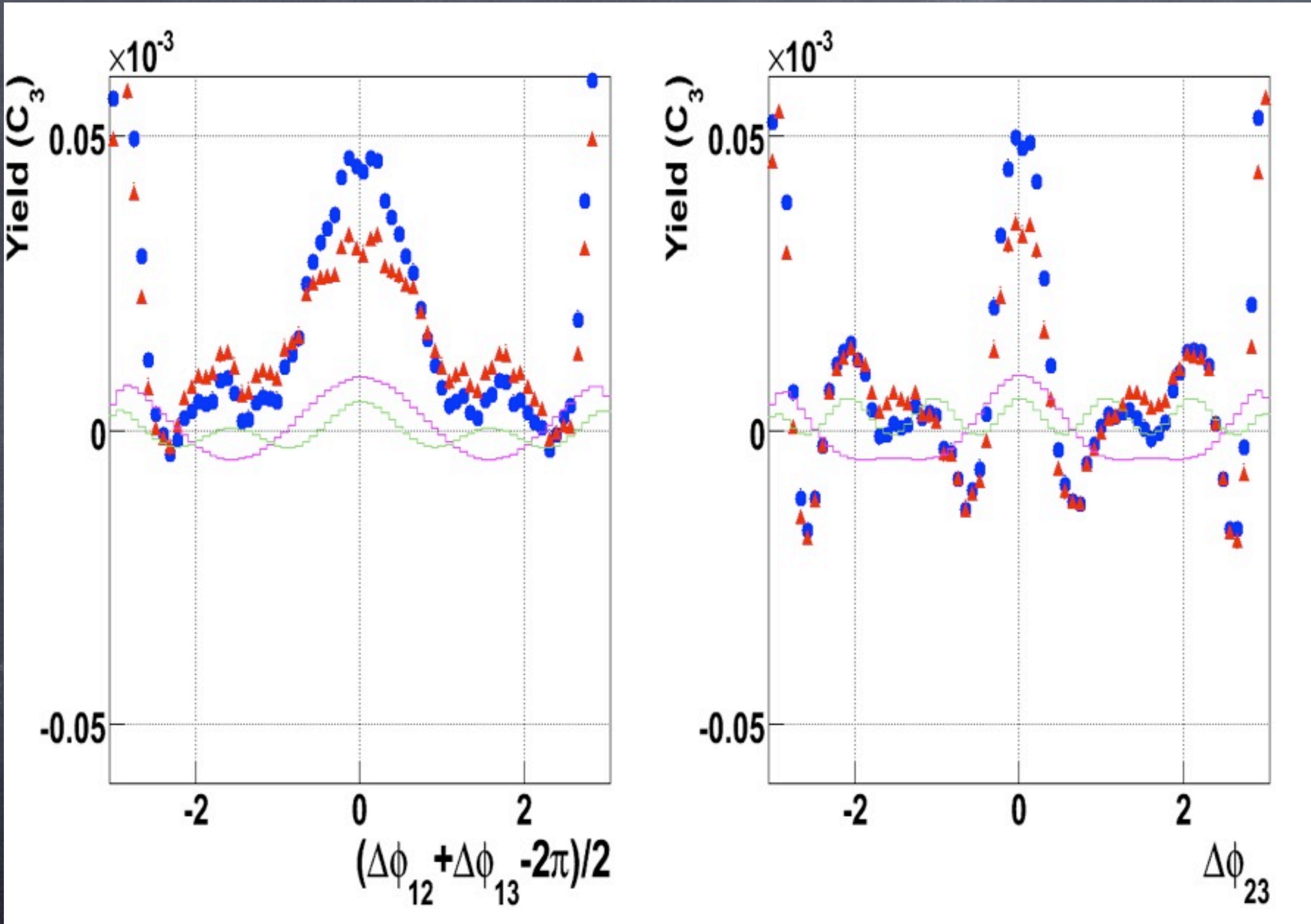
STAR Preliminary

Au+Au 200 GeV 1: 3-20 GeV, 2&3: 1-2 GeV

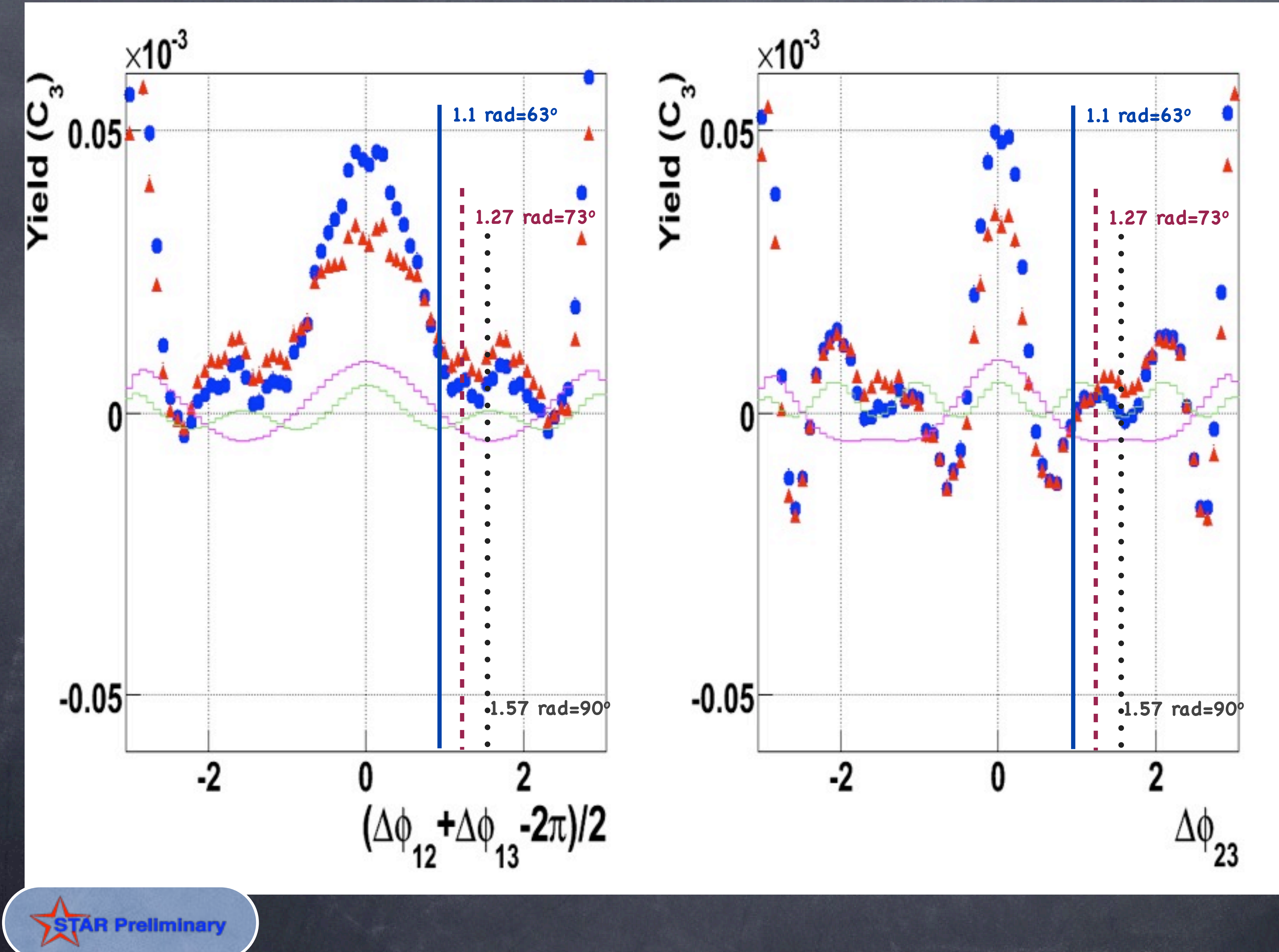


80-50% 50-30% 30-10% 10-0%

STAR Preliminary



STAR Preliminary

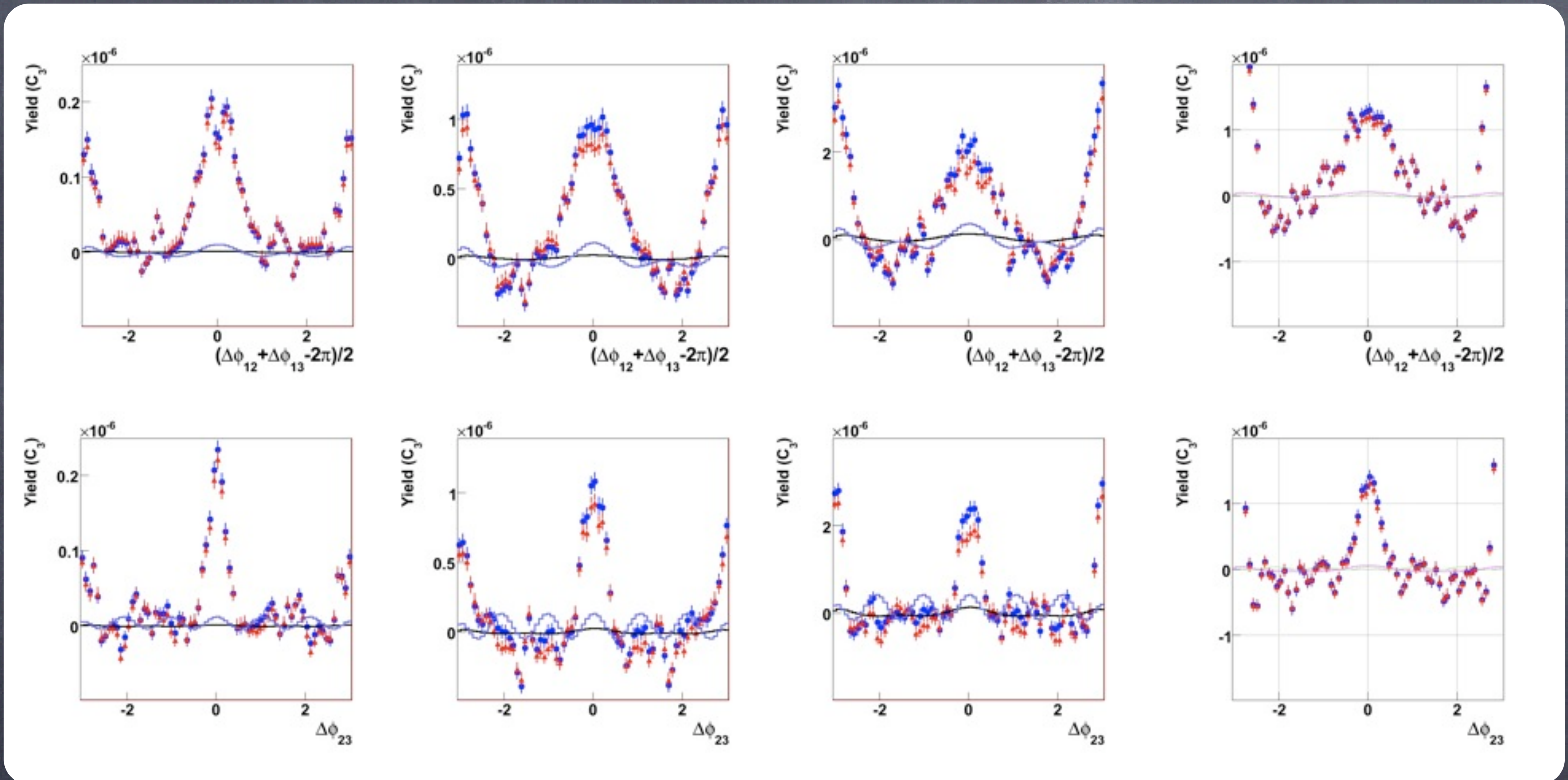


×10^-3
Yield (C_3)
0.05
0
-0.05
-2
0
2
(Δφ_12+Δφ_13-2π)/2
1.1 rad=63°
1.27 rad=73°
1.57 rad=90°
×10^-3
Yield (C_3)
0.05
0
-0.05
-2
0
2
Δφ_23
1.1 rad=63°
1.27 rad=73°
1.57 rad=90°
STAR Preliminary

Summary

- ZYAM/Model Based Methods find indications of conincal-like signal, BUT
- 3-Cumulant enables least biased search for conical emission.
- Sensitive to (approx) signal/background > ~0.1 v_2^4
- No signal found with cumulant method in Au+Au at 200 GeV.

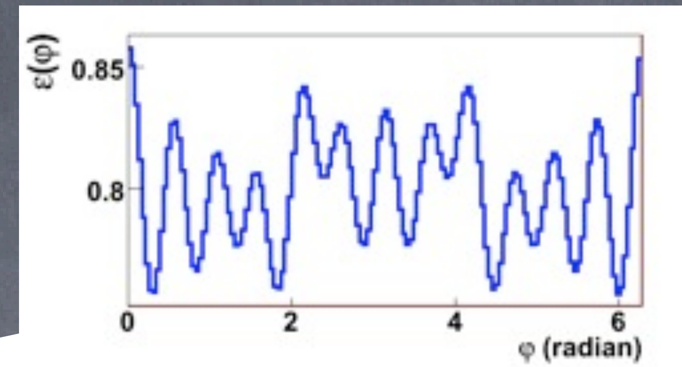
Au+Au 200 GeV 1:3-20 GeV, 2&3: 2-3 GeV



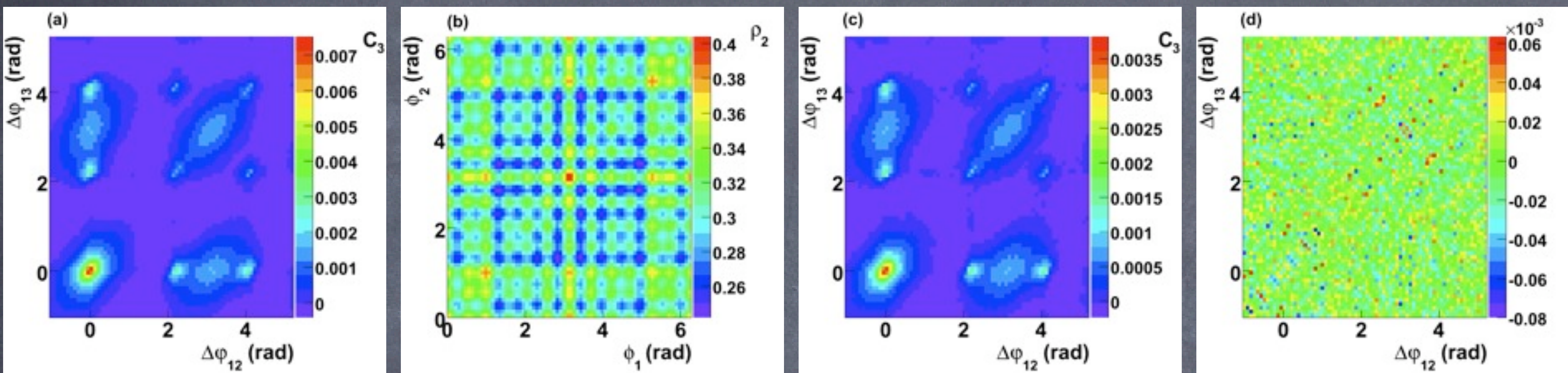
80-50% **50-30%** **30-10%** **10-0%**

STAR Preliminary

Experimental Robustness



Detection Efficiency



Simulated 3-Cumulant

2-particle density

Measured 3-Cumulant

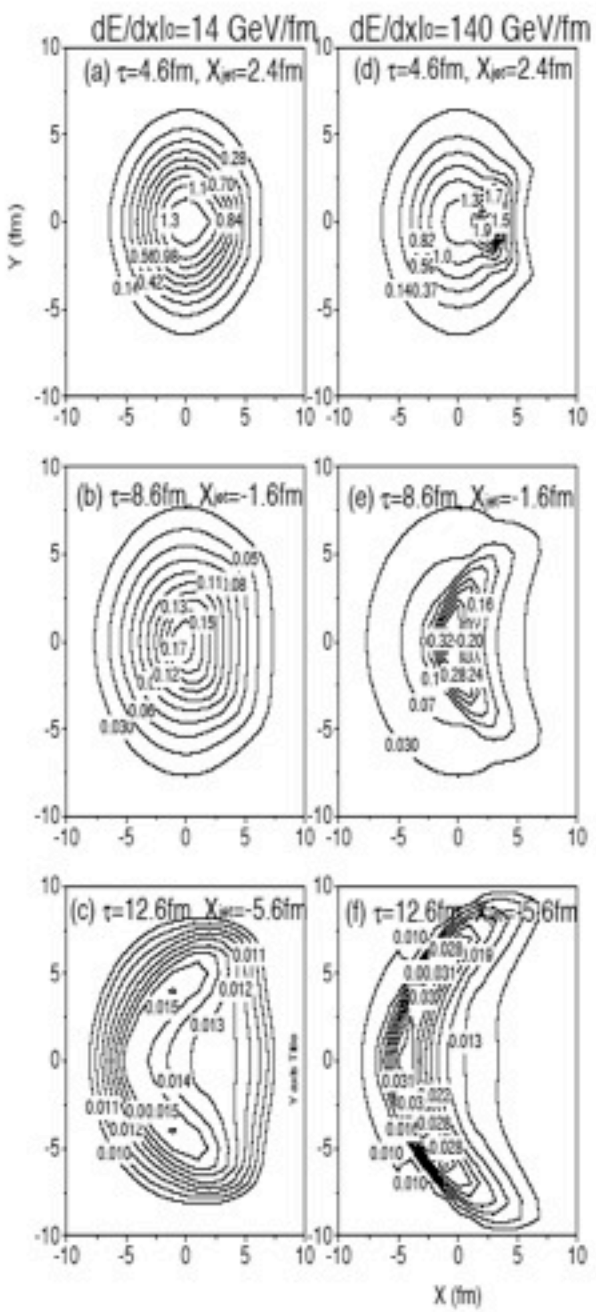
(c) - 0.8^3(a)

Measurement technique is robust!

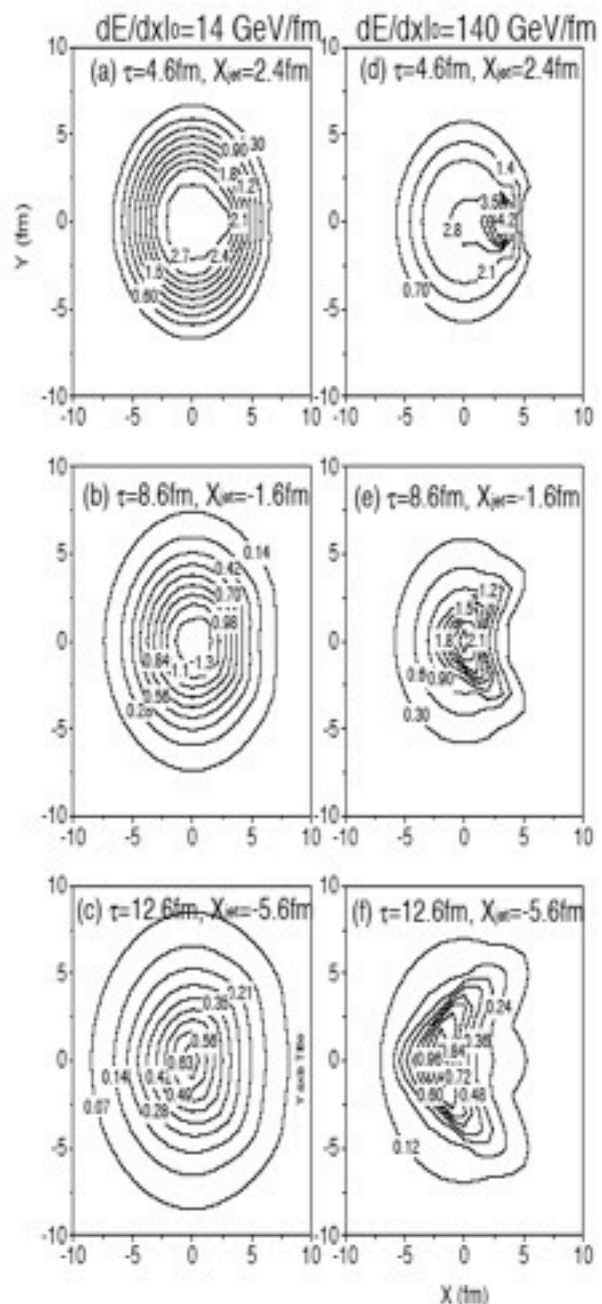
C.P., In print PRC, **arXiv:0810.1461**

Mach Cone - Hydro Calculation

A. K. Chaudhuri, U. Heinz, nucl-th/0503028



Fast Parton



v_{jet}=0.2c Fast Parton